AN AIRBORNE

REMOTE SENSING SYSTEM FOR

URBAN AIR QUALITY

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THE MITRE CORPORATION

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AN AIRBORNE REMOTE SENSING SYSTEM FOR URBAN AIR QUALITY

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ABSTRACT

Evaluation has been made of several NASA sponsored remote sensors and possible airborne platforms. Ground station data and outputs of dispersion models for SO_2 and CO for the Washington, D.C. area have been used to establish the expected performance and limitations of the remote sensors. Aircraft/sensor support requirements have been discussed. A method of optimum flight plan determination has been made. Cost trade-offs are performed. Conclusions are drawn about the implementation of such instrument packages as parts of a comprehensive air quality monitoring system in Washington.

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1.0 INTRODUCTION AND SUMMARY

The National Aeronautics and Space Administration has been developing remote sensors for the determination of the characteristics of earth and space environments for many years. Out of these development programs have come numerous sensors which have shown promise for satellite applications. Nimbus G, the earth environmental satellite to be launched in 1978, will carry in its payload several of the most worthwhile of these sensors for reporting on the global scale of air quality and/or pollution. A logical secondary question for NASA to pose was to what degree these satellite air pollution sensors might prove to be useful at lower altitudes if flown over urban areas on aircraft or helicopters. The NASA then conceived a project in which the above question could be addressed and MITRE was asked to support the project in the area of air pollution monitoring.

1.1 Objectives

The purposes of the MITRE effort may be stated with a primary objective and with several sub-objectives. Our prime objective was to look at the following NASA air quality developed sensors and analyze their use in urban air pollution monitoring.

- High Speed Interferometer (HSI)
- Lower Atmosphere Composition and Temperature Experiment (LACATE)
- Monitoring Air Pollution from a Satellite (MAPS)
- Laser Radar (LIDAR)
- Multi-Pollutant version of Carbon Monoxide Experiment, COPE (CIMATS)
- NASA/LRC Grab Sampler

Our secondary objectives were to describe the platform (aircraft or helicopter), the payload, the flight pattern, the support requirements and to the degree it was possible, the comparison of the relative costs and data quality of urban remote and in-situ air quality monitoring.

1.2 Approach

MITRE's approach to the primary objective was to examine the air quality of an urban area (Washington, D.C.) as perceived by its present ground (in-situ) air quality monitoring system, by modeling the air quality of the area using quasi-steady deterministic dispersion (transport and diffusion) models and by analysis of the above named NASA sensors. The dispersion model results were used to describe the spatial and temporal distribution of pollution over the urban area and the in-situ measurements were intended to calibrate the model, (see Section 3.0 for more details on the calibration difficulties). The characteristics of the sensors (field of view, response time, data rate and quality, etc.) were gathered and used to examine how these remote sensors responded to the magnitude and the temporal and spatial variation of the pollution over the urban area as described by the dispersion model. Each of the above listed sensors, as well as several other sensors, were modeled such that their ability to follow the variations of urban ground level pollution could be judged. The sensor modeling included operations from an airborne platform at various altitudes and velocities. Several response analysis models were developed and exercised expressly for this purpose. See Table 4-1 for summary of the resolving capability of the various sensors.

Our approach to secondary objectives - payload description, Section 5.0; platform analysis, Section 6.0; support requirements descriptions, Section 7.0; flight pattern development, Section 8.1; data quality comparisons, Section 8.2; and cost comparison, Section 9.0-followed along fairly conventional lines and are too involved for the approaches to be summarized here. See the appropriate sections of this report for these details.

1.3 Results and Conclusions

Our results regarding the primary objective, sensor analysis, were generally favorable. MAPS, LIDAR and an early version of CIMATS could prove to be useful adjuncts to the urban in-situ sampling with HSI, LACATE and the NASA Grab Sampler less so for a variety of reasons. Other sensors listed below (not in our original statement of work) show sufficient promise to warrant further consideration.

- Differential Absorption Remote Sensing (DARS)
- Gas Filter Correlation Instrument for Carbon Monoxide (GFCI)
- Gas Filter Correlation Instrument for Sulfur Dioxide (GFCI-Mod.)
- Los Angeles Regional Pollution Project (LARPP) sensor package

In particular the following conclusions can be drawn regarding these sensors.

- The CIMATS experiment should be included in any initial system since its operational capability for a low-level airborne system has been reasonably demonstrated. The COPE experiment should be discarded only if CIMATS does not become operational.

- The MAPS experiment has shown sufficient performance potential to be included. As with the previous instrument, the GFCI and modified GFCI should be included only if MAPS does not become operational.
- The DARS experiment has shown sufficient theoretical potential to warrant further agressive development for the airborne system.
- The HSI experiment has not shown sufficient potential to operate as an operational air quality measurement instrument. Its use is more suited to initial surveys of areas of interest from a slow moving or fixed platform.
- The LACATE instrument has shown very little, if any, applicability to the airborne urban measurement system. Its principal drawback is the fact that it measures a horizontal column density extending over hundreds of kilometers. This has a very low potential for detailed urban application.
- The LIDAR has considerable potential for measurement of vertical aerosol profiles and mixing heights. However, it still has a possible safety problem which requires further investigation.
- The NASA/LRC Grab Sampler has not shown sufficient overall performance to warrant inclusion in the system. However, the grab sampling concept deserves additional study.
- A contact sensor system such as that used in the EPA/LARPP program should be included in order to provide additional point measurements for interpretation of the remote instrument results.

In addition a number of general observations on the sensors were made.

- All of the passive remote sensors studied require either clear sky or optical line-of-sight from the radiation source to the instrument.
- All of the remote sensors studied produce results in the form of total column density measurement of the pollutant from the radiation source to the sensor. Interpretation of these results is necessary for comparison with dispersion model results and ground readings for surface values. Thus data reduction programs for such sensors should be developed in concert with the sensor development to be of value operationally to the ultimate user.
- All of the passive thermal ($\geq 2.8\mu$) infrared sensors have an instrument resolution capability which is limited to about $2^{o}K$. Thus these instruments cannot distinguish between IR radiation from the earth's surface and that of the air immediately adjacent to it, which is within $2^{o}K$ temperature. For a standatd atmosphere, this layer is approximately 1/2 km in altitude.
- These remote sensors produce responses which are quasi-instantaneous while both the ground stations and the dispersion model produce results which are averaged over a one hour time interval.
- The spatial resolution of the various remote sensors is on the order of one hundred meters. While the dispersion model results are on the same order of spatial resolution, the ground air quality stations measure at essentially point locations.

- Thus we have three sources of data (remote sensors, in-situ sensors, dispersion models) which are not in exact synchronization in time and space. Several sections of this document address this situation. However, there appears to be promise in developing analytical techniques for converting instantaneous column densities into ground level values which can be compared with the present modeled and ground level data.

Results regarding the secondary objectives and on our methods of performing the analysis for the primary objective (dispersion modeling) are as follows:

- Four payloads were postulated in Section 5 which could be used from an airborne platform for remote measurement of air quality. These payloads were made up from the original six sensors with and without LARPP package. Further substitutions using DARS, GFCI and GFCI-Modified should be reviewed in future efforts on this project. It was found that the most elaborate of these payloads would require a large 4-engine class fixed wing aircraft (C-54 class) or a large helicopter (Sikorsky S-65A class) to support the weight, Section 6).
- Weight was the principal factor in platform selection. Electrical power and space were generally available on many smaller platform classes, but those smaller platforms did not contain sufficient payload (weight) capacity. Platform costs generally showed that fixed wing aircraft are considerably less expensive to lease and operate than helicopters, but the overriding factor

is the ability to use NASA-owned aircraft on intra-agency agreement.

- A method for flight plan definition was developed in Section 8 based upon dispersion model CO and SO_2 pollution distributions. The areas most frequently experiencing significant levels of these pollutants were identified and the best flight plan was developed by use of a linear regression analysis. The method developed is based on division of the urban area into quadrants and a best fit linear flight segment was produced for each one. The four segments were then combined to produce one typical flight plan for the Washington area. Of course, more area division than four quadrants may be used.
- The comparable costs are presented in Section 9 for establishing a ground sampling network which could produce results equivalent in quantity and quality to that of the proposed airborne system. No attempt to get comparable data sets was made since each system (remote and ground) has its own role.
- The transport and diffusion models selected for sensor analyses included one for mobile sources and one for stationary sources. The mobile source model for carbon monoxide was run for fourteen cases using a 1-mile (1.6 km) grid over the metropolitan Washington area. In like manner, the stationary source model for sulfur dioxide was run for fourteen cases using a 1 km grid

over the same area. The results are shown and discussed in detail in Section 3.0. In general, the carbon monoxide model tended to underpredict values, compared to measured ambient air quality reported by local agencies. However, the sulfur dioxide values were underpredicted for the two Virginia monitoring sites available and overpredicted for other sites. In spite of these deviations, the patterns produced were judged to be reasonably representative of conditions prevailing in the area and could be used in the sensor analysis.

Based on the results of this study, it is concluded that the proposed airborne system can serve as a valuable adjunct to presently existing ground networks. In particular, the following conclusions can be drawn:

- The airborne system capital costs, when compared with the cost of existing ground networks, are reasonable in terms of potential value of the data produced.
- The airborne system is mobile and may be used in many localities.
- The airborne system may function as a full-time monitoring system in one locality, a part-time system in several localities, or be deployed on an as-needed basis for episodes or other significant situations. The airborne system may also assist in determining the optimum location for ground stations.
- The airborne system may be used to assist in the interpretation of air quality patterns sensed by ground (in-situ) networks.

These present in-situ networks do not describe the spatial and temporal variation in sufficient detail to answer all planning and operational air quality management questions.

- A rapid reporting air quality monitoring system with better spatial and temporal response is needed now, since air quality managers are requiring detailed data to answer the new complex source analysis requirements. The airborne remote system may fulfill much of this need. It is also possible that a set of fixed scanning remote sensors located on high towers or buildings could fill this need.
- It is recommended that NASA consider the re-engineering of all the remote sensors to provide finer spatial (less than 100 meters) and longer temporal (larger than seconds) resolution. The larger temporal resolution is to relate to present in-situ sensor output and the shorter spatial resolution is foreseen for the new complex source regulation activities.
- The initial system should address all six air pollutants for which there are air quality standards.
- The development of the remote system should be carried out with the local air quality management personnel as part of the team.
- The local air quality management personnel should be approached only through EPA Headquarters (Office of Monitoring) and then EPA Regional Office personnel. Involvement of all three levels is paramount in the acceptance of any monitoring system.

2.0 APPLICATION OF AIR QUALITY DISPERSION MODELS TO THE NATIONAL CAPITAL AIR QUALITY CONTROL REGION

The purpose of this study was to evaluate and compare the advantages and effectiveness of specific NASA air quality monitoring systems for a typical air quality control region monitoring system, namely, that of the Washington, D.C. metropolitan area. In order to accomplish this, it is necessary to have a description of the pollutant levels and patterns over the area of interest to provide a basis for establishing the actual pollution phenomena to be measured by NASA's remote sensing system. These types of data can be obtained by the execution of short-term air quality dispersion (transport and diffusion) models, and a number of such models were considered for the study.

2.1 Selection of the Models

There are two main classes of pollutants--those emitted by fixed sources and those emitted by mobile sources. The majority of emissions of the six major groups of pollutants fall into the following categories:

FIXED SOURCES	MOBILE SOURCES
particulates	carbon monoxide
sulfur oxides	hydrocarbons
oxides of nitrogen	oxidants
	oxides of nitrogen

Nitrogen oxide emissions are significant from both types of sources. In general, the pollutants listed under fixed sources do not react with other pollutants rapidly. Those listed under mobile sources have shorter reaction times, with CO being slowest to react. Thus, both sulfur dioxide and carbon monoxide were treated as non-reacting pollutants and this is a good assumption for time-distance domain of the National Capital Air Quality Control Region, (NCAQCR). It was decided that two models, one for mobile sources (carbon monoxide) and one for fixed sources (sulfur dioxide), would be selected for this task. The results of the sulfur dioxide model would show pollutant patterns somewhat typical of those for other non-reactive pollutants emitted by stationary sources, while the carbon monoxide patterns would be somewhat representative of those for other reactive pollutants emitted by mobile sources.

Previous experience in working with some of the available models was used to narrow down the list of candidate models. Mr. Bruce Turner, a National Oceanic and Atmospheric Administration employee on loan to the Environmental Protection Agency (EPA), was contacted, and he provided information about which of the models were considered most satisfactory by EPA. He also referred us to two memoranda[1,2] discussing the status of new model development and availability through the remote terminal system, Users' Network for Applied Modeling of Air Pollution (UNAMAP). This information lead MITRE and NASA to the final selection of the following models:

(1) APRAC-1A, a short-term carbon monoxide model developed by Stanford Research Institute, Menlo Park, California.

(2) SCIM, a long-term and a short-term (one hour) sulfur dioxide model developed by GEOMET, Incorporated, Rockville, Maryland.

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[1] Turner, D. B. Environmental Protection Agency, Research Triangle Park, January 2, 1973.

[2] Ruff, R. E. Environmental Protection Agency, Research Triangle Park, May 23, 1973.

2.2 Description of Each Model

2.2.1 Carbon Monoxide Model

Transportation sources are responsible for almost all carbon monoxide emitted in urban areas. Consequently, when Stanford Research Institute developed a carbon monoxide diffusion model known as APRAC-1A they designed the emissions file for only emissions from vehicular sources. When choosing this model to be run for the Washington, D.C. metropolitan area, a check was made to determine what percentage of the total CO emitted in the area came from other than vehicular sources. In the 1968 "Report for Consultation on the Washington, D.C. National Capital Interstate Air Quality Control Region," carbon monoxide emissions from fuel burning sources were shown. Using these figures it was computed that only 2% of carbon monoxide emissions in the Washington area result from non-transportation sources, and it was concluded that not including these emissions in the model would cause no significant inaccuracies in the model's predictions.

Three different types of model runs can be made, and they are known as synoptic, climatological, and grid-point.

- Synoptic Model computes "hourly concentrations as a function of time, for comparison and verification with observed concentrations and for operational applications."[1]

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[1]Mancuso, R. E. et al, "User's Manual for the APRAC-1A Urban Diffusion Model Computer Program," September 1972, page 2.

- Climatological Model computes "the frequency distribution of concentrations, for statistical prediction of the frequency of occurrence of specified high concentrations in connection with planning activities."[1]
- Grid-point Model computes "concentrations at various locations in a geographical grid, providing detailed horizontal concentration patterns for operational or planning purposes."[2]

Both the synoptic and the grid-point model forms were considered for this study, but the grid-point model was chosen because as many as 625 receptor points could be specified in one run and only as many as ten receptor points could be specified per run of the synoptic version of the model. By using the grid-point form values could be computed for the specific hours of concern and for as many points as were needed to reasonably cover the area of interest.

The emissions data required for the grid-point model are inserted in two forms:

- as emissions from vehicles traveling on the major arterial streets and freeways, and
- as secondary background emissions from vehicles traveling over the less densely traveled local and feeder streets.

Other data which the model requires are:

- coordinates of receptor locations
- gasoline consumption rates

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[1] Ibid, page 2.
[2] Ibid, page 2.

- car speeds for various road types
- peak traffic hours
- fraction of the daily traffic within each of the 24 hours by road type, and day of the week (weekdays versus Saturdays versus Sundays and holidays)
- date or dates and hour to be modeled
- temperature and pressure upper air data
- hourly surface data including cloud cover, temperature, wind speed, and wind direction.

The exact formats for inputting these data are given in the User's Manual.[1]

The model assumes all the emissions to be at ground level because they are from transportation sources. The concentration at a receptor is considered to be due only to emissions located within a logarithmically spaced segment having an arc of 22.5°. This arc is expanded to 45° within the closest one kilometer (see Figure 2-1). The closest segment extends from the receptor to 125 meters, and the farthest segment extends to 32 kilometers. All emissions within a segment are assumed to be uniformly distributed. The total emission from all highway links and parts of links that lie within a segment is averaged over the area of the segment and then the emissions from the smaller residential streets are included. Each segment is thus assigned an average emission rate to be applied throughout the segment.[2]

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[1] Ibid, pages 26-33.

[2] Ibid, page 5

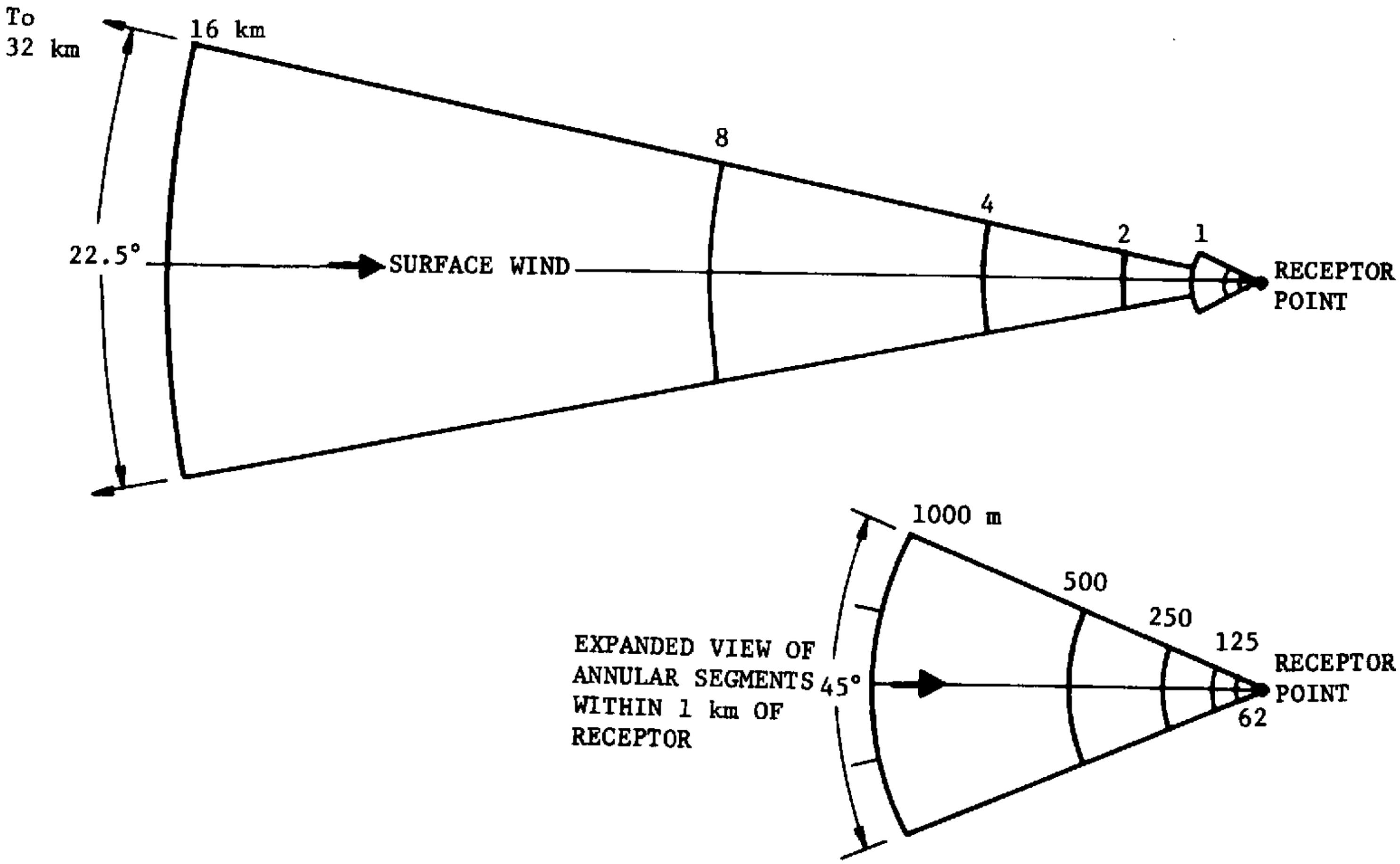

FIGURE 2-1
DIAGRAM OF SEGMENTS USED FOR SPATIAL PARTITIONING
OF EMISSIONS IN THE ARPRAC-1A MODEL

To use the emissions and other data to calculate the concentration at a receptor, equations for two types of models, Gaussian and box, have been included in the program. The box model is used when there is a limiting mixing depth determined by the vertical temperature stratification. The Gaussian model applies when there is no effective limitation to vertical mixing or when the plume has not spread sufficiently to be affected by such a limitation. "A change from the Gaussian model to the box model is made at the distance where the two would give equal values of concentration if applied to a line source."[1] The box model and Gaussian model equations are presented and discussed in a Stanford Research Institute's document.[2] Appendix D of that same document gives the equations used by the program for computation of mixing depth.

The carbon monoxide concentrations calculated by the grid-point model can be output on either a line printer, punch cards or magnetic tape. For this work the line printer was used. The results printed give the date modeled, city, number of links, number of rawinsonde (RAOB) levels, surface pressure, and the maximum and minimum surface temperatures for the day. In addition, the calculated CO value, in parts per million (ppm), is shown for each station for the hour specified. That hour, the corresponding meteorological values, and the computed mixing depth are also

[1] Ibid, page 16.

[2] Ludwig, F. L. et al, "A Practical, Multipurpose Urban Diffusion Model for Carbon Monoxide, " September 1970.

noted. Each station is identified by a sequential number, which corresponds to its position in sequence of the input receptor cards. These receptor cards contain the station's coordinates.

2.2.2 Sulfur Dioxide Model

The sulfur dioxide model used is known as the Sampled Chronological Input Model (SCIM). GEOMET, Incorporated has developed this model and two additional programs which can be used for preparation of input data required by SCIM. The first of these programs computes the mixing height and the second prepares the emission source data file. Initial runs of the GEOMET mixing height program showed a good correlation with the mixing heights computed by APRAC-1A, so the mixing height values computed by the APRAC-1A program were inserted to SCIM. This saved both computer and staff time and also assured that both the CO predicted values and the SO_2 predicted values were based on the same mixing depth which is useful when later considering the two sets of of values simultaneously to determine potential flight patterns.

The emission program was used to set up the point and area source files and the grid. Input to this program includes grid dimensions, point source data (coordinates of source, stack height, stack diameter, stack gas exit speed, stack gas exit temperature, and source emission rate) and area source data. This program converts the point source emission rates from tons per day to micrograms per second, and converts the area source emission rates from tons per square kilometer per day to tons per square meter per second. A description of the emission data used is contained in Section 2.6, Emissions Data. It should be noted that GEOMET has revised this program so that it now has the capability of transforming the EPA Implementation Planning Program (IPP) area source emission inventory directly to a uniform gridwork.

The calculation of sulfur dioxide concentrations at receptors is done in the SCIM program, using the Gaussian plume approach. This equation is presented and discussed in the User's Manual which GEOMET is preparing.[1]

In addition to the mixing height and the point and area source emissions, the model also requires:

- date or dates and hour or hours to be modeled
- sulfur dioxide decay constant
- factors for determining wind profiles of stable, neutral, or unstable atmospheres
- mean morning and afternoon mixing heights
- background concentration
- hourly surface data including ceiling height, sky condition, temperature, wind speed, and wind direction
- coordinates of receptor locations.

The exact formats for these data are given in the User's Manual.

The sulfur dioxide concentrations calculated for each specified receptor are available as output on both a line printer and on magnetic tape. The output includes the input parameters (mean morning and afternoon mixing heights, background concentration, etc.), listing of the point

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[1] Koch, R. C. and G. H. Stadsklev, "A User's Manual for the Sampled Chronological Input Model (SCIM)"--draft, August 1973.

source data, listing of the area source data, the receptor coordinates, and the calculated receptor concentrations.

2.3 Air Quality Data

Several information sources were used in order to compile a complete and up-to-date list of sites in Virginia, Maryland, and Washington, D.C. which continuously monitor carbon monoxide and sulfur dioxide. The site inventory of the National Aerometric Data Bank (NADB) was used to prepare a preliminary list of sites in the National Capital Air Quality Control Region (NCAQCR). This list was then compared to the information appearing in the three state implementation plans which apply to this AQCR, and revised accordingly. In order to further verify the resulting list of sites the Metropolitan Washington Council of Governments (COG) was consulted. All the air pollution control agencies in the area of interest, cooperate with COG, so COG's information is considered more reliable than the first two sources consulted. The final list of sites is a combination of information from all three sources and appears in Table 2-1.

Data reported by these sites were obtained from the NADB files. These files did not contain any data from the four Maryland air monitoring system (AIRMON) sites. Mr. Carter of the Maryland State Department of Health and Hygiene was contacted, and he explained that because the sites had only begun operation in early 1972, their data did not yet appear in the NADB files. He was able to provide copies of both the carbon monoxide and sulfur dioxide data for all four of these sites. A sample of the data which he provided is shown in Figure 2-2.

TABLE 2-1

HOURLY CO AND SO_2 MONITORING SITES IN THE NCAQCR*

STATE	SITE LOCATION
District of Columbia	CAMP - 1st & New Jersey Ave, N.W.
	DC General Hospital
Virginia	Montgomery Wards - 7 Corners
	Alexandria Health Department
	Rosenthal Chevy, Shirlington
Maryland	NIH - Wisconsin Ave**
	Silver Spring**
	Gaithersburg Lab***
	RT 410-Hyattsville**
	Federal Center-Suitland**

*All stations monitor CO and SO_2 except Gaithersburg Lab which monitors only CO.

**Maryland AIRMON Sites.

***Beyond grid being mapped.

DATE RUN-10/17/72 MSDAQC REGION-4

STATION 211560001 F01 SUITLAND PRINCE GEORGE V.G.-0819 H.G. 0371

AIRMON 3 SUITLAND PKWY AIRMON

APRIL 1972 CARBON MONOXIDE 8SCK AT INFRA RED PPM POLLUTANT-CODE 4210111

DAY	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	MAXIMUM HOUR	MAXIMUM 8-HR	DAILY AVER	DAILY CNT
										HOUR BEGINNING AT																		
01	2.	1.	1.	1.	1.	1.	1.	1.	0.	C.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	2.	1.	0.	24
02	0.	0.	0.	0.	0.	0.	0.	0.	0.	C.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.		0.	0.	0.	0.	23
03	0.	0.	0.	0.	0.	0.	1.	1.	1.	C.	0.	0.	0.	0.	0.		0.	1.	1.	4.	3.	1.	1.	1.	4.	2.	1.	23
04	0.	0.	0.	0.	0.	0.	1.	2.	2.	1.	1.	1.	1.	1.	1.	1.	2.	1.	1.	2.	1.	1.	1.	2.	2.	1.	1.	24
05	1.	1.	1.	1.	1.	2.	3.	2.	1.	C.	0.	0.	0.	C.	0.	0.	1.	0.	0.	1.	1.	1.	1.	0.	3.	2.	1.	24
06	0.	0.	0.	0.	C.	0.	0.	1.	1.	C.	0.	2.	3.	C.	0.	0.	0.	0.	0.	0.	0.				3.	1.	C.	21
07																	0.			6.	1.	1.	1.	0.	6.	2.	2.	C6
08	1.	0.	1.	1.	1.	1.	1.	1.	0.	C.	1.	0.	0.	0.	0.	1.	1.	1.	1.	1.	1.	1.	1.	1.	1.	1.	1.	24
09	1.	1.	1.	1.	0.	0.	0.	0.	0.	C.	0.	0.	1.	0.	0.	0.	0.	0.	0.	1.	1.	2.	2.	1.	2.	1.	1.	24
10	1.	1.	1.	1.	1.	1.	2.	1.	1.	1.	1.	1.	1.	0.	0.	0.	0.	1.	1.	1.	0.	0.	0.	0.	2.	1.	1.	24
11	1.	1.	0.	0.	0.	0.	0.	1.	2.	2.	2.	1.	1.	0.	0.	0.	1.	1.	1.	2.	2.		1.	0.	2.	1.	1.	23
12	0.	0.	0.	0.	0.	0.	0.	2.	2.	1.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	2.	1.	C.	24
13	0.	0.	0.	0.	0.	0.	0.	0.	1.	C.	0.	1.	1.	1.	1.	1.	2.	1.		1.	1.	1.	1.	0.	2.	1.	1.	23
14	0.	0.	0.	0.	0.	0.	1.	2.	1.					2.	0.	0.	1.	1.	1.	1.	1.	0.	0.	0.	2.	1.	1.	20
15	0.	0.	0.	0.	0.	0.	0.	0.	0.	C.	0.	1.	0.	0.	0.	2.	2.	2.	3.	2.	1.	1.	0.	2.	3.	2.	1.	24
16	2.	1.	1.	2.	2.	1.	0.	1.	1.	1.	1.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	2.	2.	1.	24
17	0.	0.	0.	0.	0.	0.	0.	1.	1.	C.	0.	0.	1.	1.	1.	1.	1.	2.	1.	2.	2.	2.	2.	2.	2.	2.	1.	24
18	2.	2.	1.	2.	2.	3.	3.	2.	0.	C.	0.	0.	0.	1.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	3.	2.	1.	24
19	0.	0.	0.	0.	0.	0.	0.	0.	0.	C.	0.	0.	0.	0.	0.	0.	1.	0.	C.	0.	0.	0.	0.	0.	1.	0.	0.	24
20	0.	0.	0.	0.	0.	0.	0.	0.	0.	C.	0.	1.	0.	0.	0.	0.	2.	2.	0.	0.	0.	0.	0.	0.	2.	1.	0.	24
21	0.	0.	0.	0.	0.	0.	0.	0.	0.	C.	0.	0.	0.	0.	0.	0.	0.	1.	1.	0.	0.	0.	0.	0.	1.	0.	0.	24
22	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.	1.	1.	1.	1.	1.	1.	1.	1.	3.	5.	5.	5.	5.	5.	5.	5.	2.	24
23	5.	5.	5.	5.	2.	0.	0.	0.	0.	C.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	5.	4.	1.	24
24	0.	0.	0.	0.	0.	1.	1.	1.	1.	C.	0.	1.	0.	1.	0.	1.	2.	2.	1.	2.	5.	6.	6.	6.	6.	5.	2.	24
25	6.	4.	3.	2.	1.	1.	2.	1.	0.	C.	1.	1.	0.	0.	0.	0.				1.	1.	3.	3.		6.	3.	2.	20
26	0.	0.	0.	0.	0.	0.	C.	0.	0.	C.	0.	0.	0.	0.	0.	0.	0.	0.	0.		1.	1.	0.	0.	1.	0.	C.	23
27	0.	0.	0.	0.	0.	0.	0.	1.		C.	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.	3.	2.	2.	1.	3.	2.	0.	23
28	2.	3.	2.	1.	3.	3.	3.	2.	1.	6.	~~62.~~	~~47.~~	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	~~62.~~	~~10.~~	6.	24
29	0.	1.	1.	1.	1.	3.	2.	1.	1.	1.		1.	0.	1.	1.										3.	1.	1.	14
30																												
ARITH. AVER	0.	0.	0.	0.	0.	0.	0.	0.	0.	C.	2.	2.	0.	0.	0.	0.	0.	0.	0.	1.	1.	1.	1.	0.				
MAXIMUM HR.	6.	5.	5.	5.	3.	3.	3.	2.	2.	6.	62.	47.	3.	2.	1.	2.	2.	2.	3.	6.	5.	6.	6.	5.				
PEAK READ	9.	8.	6.	5.	5.	7.	8.	5.	4.	62.	62.	62.	4.	61.	3.	3.	4.	5.	5.	7.	8.	8.	8.	8.				

MONTHLY ARITHMETIC MEAN- 00.826 HOURLY RECORD COUNT-651 PERCENT AVAILABLE DATA- 90

STD. DEV. 3.221 GEO-MEAN .544 STD GEO DEV 4.351 HOUR MAX RD.- 62. PEAK MAX RD.- 62. 8-HR MAXIMUM READ- 16.

FIGURE 2-2
MARYLAND AIR QUALITY DATA REPORT FORMAT

2.4 Selection of Days to be Modeled

Numerous factors had to be considered when selecting the days to be modeled. First of all, dates prior to 1971 were disregarded as not being sufficiently current. Much of the 1973 air quality data has not yet been tabulated and entered into the National Aerometric Data Bank. Consequently, the 1971 and 1972 calendar years were considered the best candidates for modeling dates.

The wind direction and wind speed are important factors in determining the values the model predicts. Low ventilation days were sought for modeling. Meteorological data were obtained from the National Climatic Center in Asheville, North Carolina. These data were reviewed to determine low ventilation days which during most hours of the day had the wind coming from one direction either northwest, northeast, southwest, or southeast. In addition, only days with very little or no precipitation were included. This review yielded a list of candidate dates for modeling.

In order to make a judgment regarding the accuracy of the values predicted by the model, actual values recorded by monitoring equipment operating within the area of interest were needed for comparison. The air quality data for sites in the NCAQCR were checked for candidate dates to identify those days for which all monitoring sites were not reporting data and those dates for which data were not reported for all 24 hours.

Those days with little reported air quality data were eliminated. Next all holidays and weekends were omitted because of variations in quantity of traffic and flow patterns. From the resulting revised list of possible modeling days, one day was selected for each wind direction. The basis for these decisions was the lowest wind speeds. The four dates chosen were 24 April, 8 June, 25 September, and 4 December 1972.

For the sulfur dioxide model,no particular time of the day is of special interest. Because the carbon monoxide emissions are related to the volume of automobile traffic, rush hours are of particular interest for the carbon monoxide model. Consequently, a morning rush hour, 7:00 A.M., was chosen as the time for which the models would be executed in these four dates.

During 1972, four air pollution alerts were called by the Metropolitan Washington Council of Governments. The dates of these alerts were compared to the dates which MITRE chose for modeling. None of the dates were the same. It was decided that the model should be executed for at least one of the alert days in addition to the days already chosen. To select the alert day to be modeled, initially wind speed and direction were not considered. Rather, the number of hourly carbon monoxide and sulfur dioxide measurements recorded on each day were considered and, as before, Saturdays, Sundays, and holidays were omitted from consideration. Tables 2-2 and 2-3 summarize the number of hourly air quality observations reported for the two pollutants of interest. July 18 (Tuesday) and July 24 (Monday) were the best candidates, each having five sites reporting data for 20 hours or more. At this point, the wind speeds during these two days were checked, and July 18 proved to have lower wind speeds and was thus chosen as the alert day to be modeled.

TABLE 2-2

NUMBER OF HOURS OF RECORDED CO DATA DURING 1972 AIR

POLLUTION ALERT PERIODS

DATE	SITE							
	CAMP	DC GENERAL	WARDS	ALEXANDRIA HEALTH DEPT	NIH	SILVER SPRING	RT410	FEDERAL CENTER
Monday, July 17	0	0	23	0	22	22	0	22
Tuesday, July 18	0	0	24	0	21	23	0	21
Wednesday, July 19	0	0	22	0	23	23	0	23
Thursday, July 20	0	0	24	0	24	14	0	19
Friday, July 21	0	0	24	0	9	0	0	24
Saturday, July 22	0	0	24	0	0	0	0	11
Sunday, July 23	0	0	24	0	0	0	0	12
Monday, July 24	0	0	24	0	0	0	0	22
Monday, August 14	10	24	24	0	0	0	0	0
Tuesday, August 15	0	24	24	0	0	0	0	0
Thursday, August 24	23	24	24	0	0	0	0	0
Friday, August 25	23	24	23	0	7	9	8	9
Saturday, August 26	23	24	24	0	16	24	15	24
Sunday, August 27	23	24	18	0	24	17	0	24
Friday, September 8	23	0	24	0	24	24	24	24

TABLE 2-3

NUMBER OF HOURS OF RECORDED SO_2 DATA DURING 1972

AIR POLLUTION ALERT PERIODS

DATE	SITE							
	CAMP	DC GENERAL	WARDS	ALEXANDRIA HEALTH DEPT	NIH	SILVER SPRING	RT410	FEDERAL CENTER
Monday, July 17	23	0	11	14	16	18	0	9
Tuesday, July 18	23	0	24	24	18	22	0	20
Wednesday, July 19	23	0	22	13	15	23	0	23
Thursday, July 20	23	0	23	12	24	24	0	24
Friday, July 21	23	0	24	12	24	24	0	24
Saturday, July 22	23	24	21	24	22	3	0	22
Sunday, July 23	23	23	20	21	24	0	0	24
Monday, July 24	21	23	20	23	22	2	0	22
Monday, August 14	10	24	22	10	0	0	0	0
Tuesday, August 15	0	24	23	15	0	0	0	0
Thursday, August 24	11	24	0	14	0	0	0	0
Friday, August 25	5	24	0	19	9	9	8	9
Saturday, August 26	12	24	0	14	1	24	24	24
Sunday, August 27	23	24	0	24	0	24	24	24
Friday, September 8	9	0	0	24	23	24	23	12

As in the case of the other dates, the models were executed for 7:00 a.m. In order to obtain a closer look at the changes in pollution magnitude and patterns occurring throughout this alert day, the models, were run for nine additional times:

A.M.	P.M.
1:00	1:00
4:00	4:00
8:00	6:00
10:00	7:00
	10:00

These times were selected at three hour intervals and the peak traffic hours of 8:00 A.M. and 6:00 P.M. were added.

Although data spanning an entire calendar year were considered, the modeling dates chosen only cover an eight month period (April 24 through December 4). Based on the meteorological data reported for Washington, D.C., December 4 can be considered a typical winter day and April 24 a typical spring day, so the dates modeled do indeed span all seasons of the year.

2.5 Meteorological Data

Both the carbon monoxide model and the sulfur dioxide model required similar meteorological data. These data were surface data for Washington National Airport and upper air data for Dulles Airport.

Prior to acquiring these data, MITRE checked the National Weather Service's publication "Monthly Weather Review" for the years 1968 through 1972 to see if the weather patterns which occurred in Washington

D.C., were generally typical of this area's weather. No significant long term abnormalities in the weather or climate were found, so it was concluded that any test dates selected in 1972 would be quasi-representative of typical Washington conditions. The procedure for the selection of test dates was discussed in the previous section of this paper.

The carbon monoxide model required temperature and pressure sounding data for 1200 GMT for both significant and standard levels. In addition, for each hour of the day the following surface data must be used:

- cloud cover in tenths
- temperature in degrees Fahrenheit
- wind direction in tens of degrees from north
- wind speed in knots

All of these data could be taken directly from the information received from the NOAA National Climatic Center.

The sulfur dioxide model has been designed to read the WBAN hourly surface observations in National Climatic Center Deck 144 format. The input program which computes the mixing height, reads two files of RAOB data, Card Deck 645, ROAB Constant Pressure Levels and Card Deck 505, RAOB Significant Levels. The meteorological data were obtained in printout form for the APRAC work before it was decided to use the SCIM sulfur dioxide model. These data include the temperature and relative humidity at every 50 mb pressure level between 1000, and 500 mb plus all significant pressure levels up to 500 mb. Since the upper air sounding printouts only report for the standard levels of 1000, 850, 700 and 500 mb and the significant levels, it was necessary to plot the sounding to obtain all the desired data. This was also true for the relative humidity since moisture data on the sounding printout is reported as the dew point depression. Figure 2-3 shows a typical plot on a Skew T, log p diagram of the sounding data for two of the days of interest. The relative humidity for each level was obtained by reading the mixing ratio (w) and the saturation mixing ratio (w_s) for each level and computing the ratio w/w_s which equals the relative humidity.

2.6 Emissions Data

2.6.1 Carbon Monoxide Model

The basis for this model is the carbon monoxide emissions from a network of 737 traffic road segments or links. Each of these links must be assigned an average daily traffic volume based on historical, current, or forecast data obtained from appropriate traffic agencies. The average daily traffic volume is expressed in vehicles per day. Traffic link data for the Washington, D. C. metropolitan area were received from SRI along with the program listing. Because of the large amount of time and energy required to prepare such traffic data for use in APRAC, the SRI data were used with a growth factor applied to up-date them.

The SRI data were based on 1965 traffic figures, and needed to be extrapolated to 1972 levels, because the model was going to be exercised for 1972 dates. Traffic figures acquired from both COG and the U. S. Department of Transportation (DOT) were used to compute an appropriate growth factor. COG's most up-to-date data are for 1968. While DOT

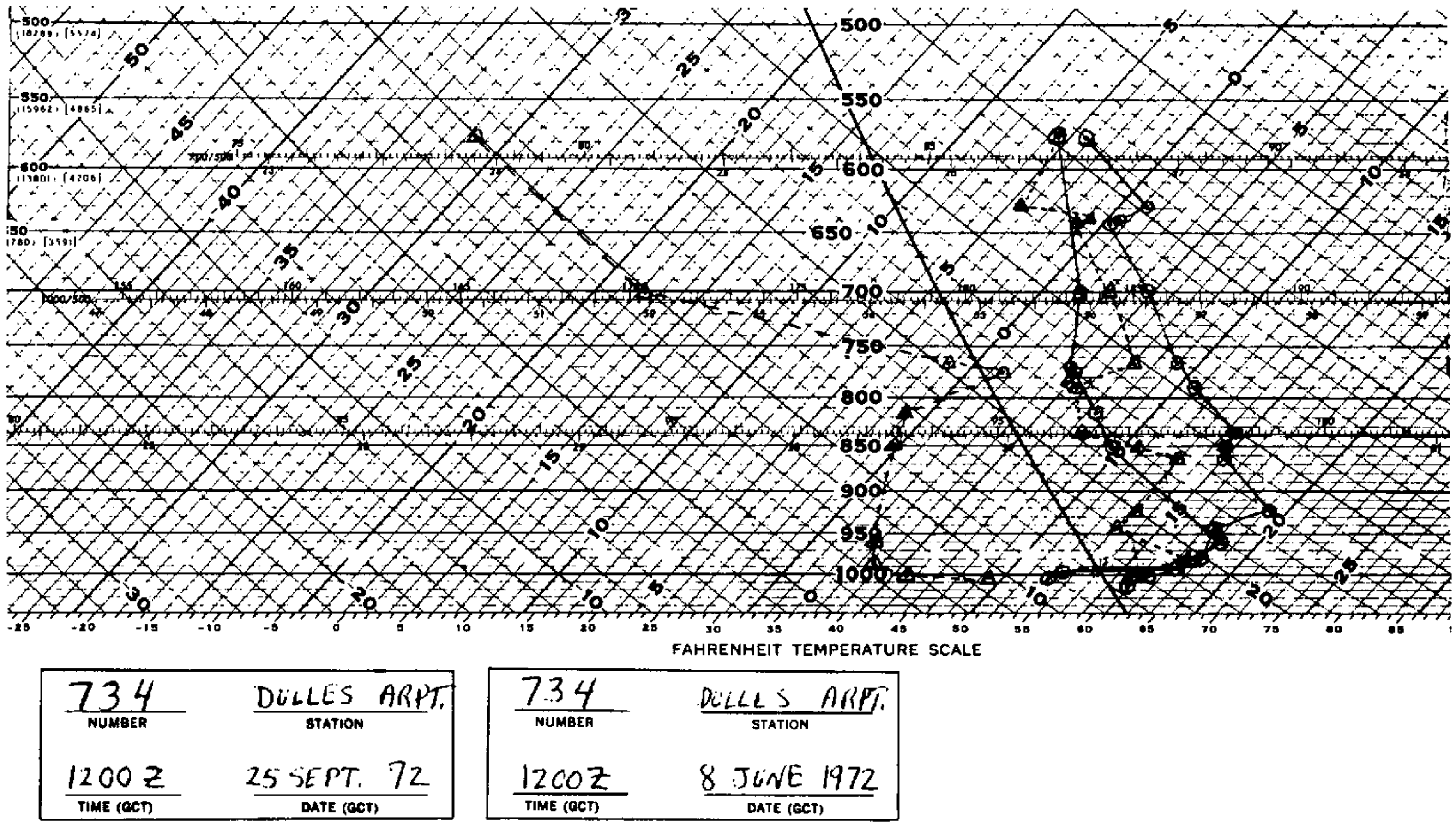

FIGURE 2-3
EXAMPLES OF UPPER AIR SOUNDINGS USED IN THE DIFFUSION MODELING

has more current data, they are summarized by state rather than by metropolitan area. Thus it was necessary to estimate a growth factor for the period of interest and the area of interest based primarily on data for Washington, D.C. The following figures were obtained from DOT and represent the traffic volume in the District of Columbia.

Year	VMT*/YR	VMT/DAY	% Change from Previous Tabulated Year
1965	2,481 million	6,797,200	-
1968	2,731 million	7,482,100	+ 10.1
1972	2,945 million	8,068,400	+ 7.8

In order to calculate the total number of VMT/day based on the SRI data, MITRE took the length of each traffic link and multiplied this by the number of vehicles per day on the link and summed these values for all traffic links. The result was 16,960,280 VMT/day. If the 10.1% increase is assumed for the entire area under consideration, the total VMT/day in 1968 for the area would be 18,656,308. This figure is slightly greater than the 18,158,308 VMT/day reported by COG for a roughly comparable area. Although it is not completely accurate (3% difference) to assume the same growth rate for the surrounding suburbs, as for Washington, the result obtained by doing so, does seem reasonable. Thus the percent change (19%) of VMT/day in Washington over the 1965 to 1972 period was used as the growth factor. This 19% factor was applied to the number of vehicles per day for each link.

Secondary traffic data, handled as area sources, could not be provided for Washington by SRI. They suggested that the city's total

*Vehicle miles traveled

amount of secondary traffic as a percent of primary traffic was between 2 and 3 percent. A report prepared by COG[1] was consulted as a second source of such information. The figures obtained that the VMT on collector and local streets is 12% of the total VMT on arterials. This 12% figure was used for the modeling run. Based on maps from the same COG report, MITRE estimated, for each of the 216 grid squares, the percent of the city's total secondary traffic occuring within the square. Because the program will only accept whole numbers between 0 and 100, most of the outlying grid squares were assigned zero values.
program will only accept whole numbers between 0 and 100, most of the outlying grid squares were assigned zero values.

SRI did not compute for Washington the fraction of daily traffic occurring within each hour of the day. The NCAQCR Implementation Plan for the control of carbon monoxide indicated that 14.55% of all daily traffic occurs between the hours of 6 and 9 A.M., but it does not say on what the figure is based, whether it is for an average day or a weekday. Using that figure to estimate the percent of daily traffic occurring during other hours of the day and considering that 6 to 9 A.M. are peak traffic hours, little variation throughout the day could be shown. All hours would have to have about 4% of the daily traffic. To create a distribution which was felt would better reflect the fluctuations which occur in traffic during hours of a typical weekday, MITRE increased the 6 to 9 A.M. percentage to 19.5% and assumed the same figure for the 4 P.M. to 7 P.M. peak hours. The remaining percentage of traffic was distributed over the other hours of the day, assuming that the least

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[1] Sarros, Ronald G., "Existing Transportation Systems in the Washington Metropolitan Area", June 1972.

traffic would occur between the hours of midnight and 6 A.M. The complete hourly distribution which resulted is shown in Table 2-4 and is the one which was used for the MITRE runs of the carbon monoxide model.

2.6.2 Sulfur Dioxide Model

The sulfur dioxide model (SCIM) requires both area source emissions and point source emissions as input. Area source data were obtained from two organizations, namely EPA and the D. C. air and Water Pollution Control Office. Area source data were also obtained from the State of Maryland but were found to be incomplete, incompatible and unintelligible. The NEDS* file for the Washington AQCR, obtained from EPA gives the total SO_2 area emissions for each county or city. The D.C. SO_2 data were given for each square kilometer in the District based on the UTM grid. However, a substantial discrepancy exists between the NEDS total for D. C. and the D. C. Control Office total for D. C. Discussions with D. C. and EPA personnel led us to the conclusion that the NEDS totals were more likely to be accurate. However, it was also concluded that the proportional distribution of the total among the various grid squares by the D. C. Control Office could be used to apportion the NEDS total to the various grid squares. The apportioning procedure was used on the NEDS total to obtain the breakout for D. C. area sources. The D. C. area source emissions were prepared for each one square kilometer area covered by the grid.

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* NEDS is the Environmental Protection Agency's National Emission Data System.

TABLE 2-4

ESTIMATED PERCENT OF DAILY TRAFFIC
OCCURRING WITHIN EACH HOUR OF A DAY

Hour	% daily traffic
0000	2.0
0100	1.5
0200	1.5
0300	1.5
0400	1.5
0500	1.5
0600	6.5
0700	6.5
0800	6.5
0900	4.5
1000	4.5
1100	4.5
1200	4.5
1300	4.5
1400	4.5
1500	4.5
1600	6.5
1700	6.5
1800	6.5
1900	4.5
2000	4.0
2100	4.0
2200	4.0
2300	3.5

Since only NEDS totals were available for Virginia and Maryland counties and cities, the following procedure was used in those areas. The total number of square kilometers was determined for each city and county listed below.

Montgomery Co.	1267 sq. km.
Prince George's Co.	1242 sq. km.
Alexandria	38 sq. km.
Arlington	67 sq. km.
Fairfax Co.	1021 sq. km.
Fairfax City	15 sq. km.

To simplify computations MITRE combined Fairfax County and Fairfax City and treated them as one area. Next it was decided to use 0.001 tons/day (0.9 Kg/day) of emissions for each square kilometer lying outside of our grid and for each one lying inside the grid but judged to contribute minimal SO_2 area source emissions. The total number of such squares is shown below:

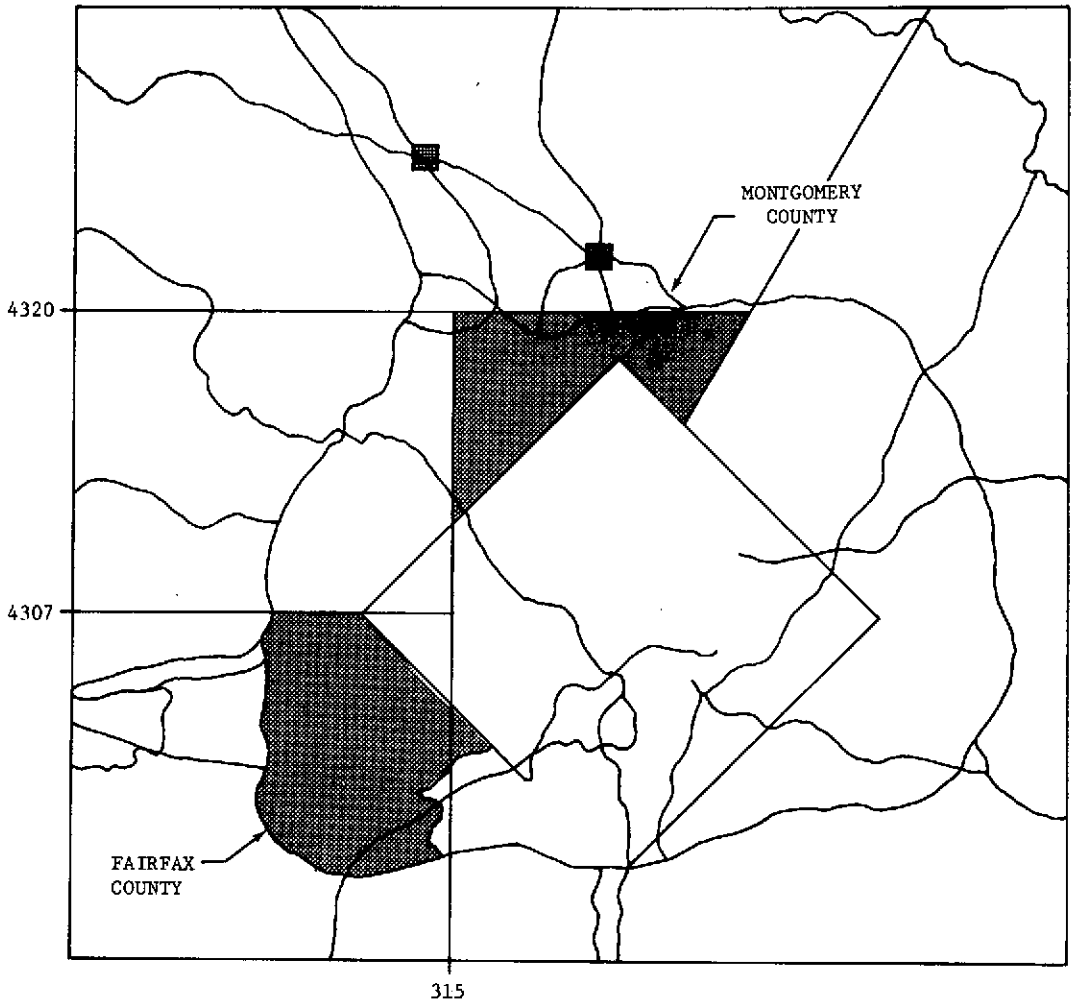
Montgomery Co.	1016
Prince George's Co.	967
Alexandria	0
Arlington	4
Fairfax Co. & City	723

The contribution from these squares was subtracted from the total emissions shown by the NEDS file for each of the corresponding areas. We felt that there would be little variation in area source emissions between the various grid squares covering Arlington, so the remaining tons of emissions for Arlington were equally distributed over the remaining grid squares. The same procedure was used for Alexandria and Prince George's County.

In Fairfax County and City, those grid squares which lie totally or mostly inside the beltway (Route I-495) and below the 4307 grid line (see Figure 2-4) were considered to have higher area source emissions than the other remaining grid squares. An emission rate of 0.056 tons/day (50.8 kg/day) was applied to squares below the 4307 grid line and inside the beltway. This value was chosen as a typical value from the Washington data for an area comparable to these sections of Fairfax County and City. The remaining emissions were equally distributed over the remaining area, resulting in an emission rate of 0.019 tons/day (17.2kg/day). This value was thus used for the remaining squares in Fairfax County and City.

Similarly, the rest of the grid squares in Montgomery County were divided into two groups, those thought to have higher area source emissions and those considered to have moderate area source emissions. The squares which were assigned the higher area source emissions were to the right of the 315 grid line and below the 4320 grid line, and the squares whose lower left-hand coordinates were (413,4327) (414,4327) and (321, 4322) (see Figure 2-4). The emission rate for these squares was again 0.056 tons/day (50.8kg/day), and the rate for the other grid squares was 0.024 tons/day (21.8kg/day).

Since space heating is a major source of sulfur dioxide pollution, ambient temperatures are closely related to emissions. For area sources,



AREA EMISSIONS FOR SHADED AREAS = 0.055 TON/DAY PER SQ.KM.

FIGURE 2-4
HIGH EMISSION AREA SOURCES FOR FAIRFAX COUNTY
AND MONTGOMERY COUNTY

the model takes this into consideration, and uses the input area source emission rates to estimate emission rates as a function of temperature and hour of the day. However, point source emission rates are treated as constant. This means that the model user must make such adjustments when preparing the point source data.

The NEDS point source file was used to prepare the point source data required by the model. Only those sources emitting more than 100 tons SO_2/year were included.

The model requires that emissions be input in units of tons/day, rather than in tons/year. To make this conversion, one should know the number of days per year which the unit operates as well as variations in utilization which occur throughout the year. This information is not presently available in the NEDS file, so several assumptions were made in order to have a basis for converting the data. These assumptions were:

(a) There are three types of point sources: power plants, incinerators, and heating units.

(b) Power plants and incinerators operate 365 days per year.

(c) Average daily emissions are constant throughout the year for power plants and incinerators.

(d) Operation and, in turn, emissions from heating units are directly related to the departure of the ambient temperature from $65^{\circ}F$ ($18.3^{\circ}C$).

Using the above assumptions, MITRE was able to convert the total annual emissions of power plants and incinerators to tons/day, simply by dividing the total by 365. The resulting value was considered to be the emission rate for all days of the year.

For heating units, more calculations were required. The average ambient temperatures for each month of 1972 and for each month of the 30-year average were recorded and their negative departure from 65°F (18.3°C) was then computed. These deviations and their percent of the total are shown in Table 2-5. The correlation between the 1972 figures and those for the 30-year average (see Figure 2-5) is good. The 1972 figures were used for these calculations.

Based on the previously stated assumption that the operation of heating units is directly related to the departure of the temperature from 65°F (19.3°C), and the data in Table 2-5 showing no days with temperatures below 65°F during May, June, July, August, and September, it is concluded that Washington area heating units are not in operation during those five months. Consequently, heating unit point sources were removed from the emission file, whenever the model was executed for a date occurring in one of those months.

For each of the other seven months, average daily emissions were computed in the following manner:

$$E_D = \frac{E_A(P)}{D}$$

where: E_D = Daily emissions for the month
E_A = Annual emissions
P = % of total 1972 annual departure from 65°F for the month
D = Number of days in the month.

TABLE 2-5*

NEGATIVE DEPARTURE OF MEAN MONTHLY TEMPERATURE

AT NATIONAL AIRPORT FROM 65°F

	DEGREES MEAN MONTHLY TEMP. IS BELOW 65°		% OF TOTAL ANNUAL DEPARTURE	
MONTH	1972	30 YEAR AVERAGE	1972	30 YEAR AVERAGE
January	26.5	28.1	20	21
February	28.5	27.2	21	20
March	19.4	20.2	14	15
April	10.9	9.3	8	7
May	0.4	0	0	0
June	0	0	0	0
July	0	0	0	0
August	0	0	0	0
September	0	0	0	0
October	9.0	6.0	7	4
November	18.2	17.3	13	13
December	21.4	26.9	16	20
	134.3	135.00	99	100

* Based on data from National Weather Service

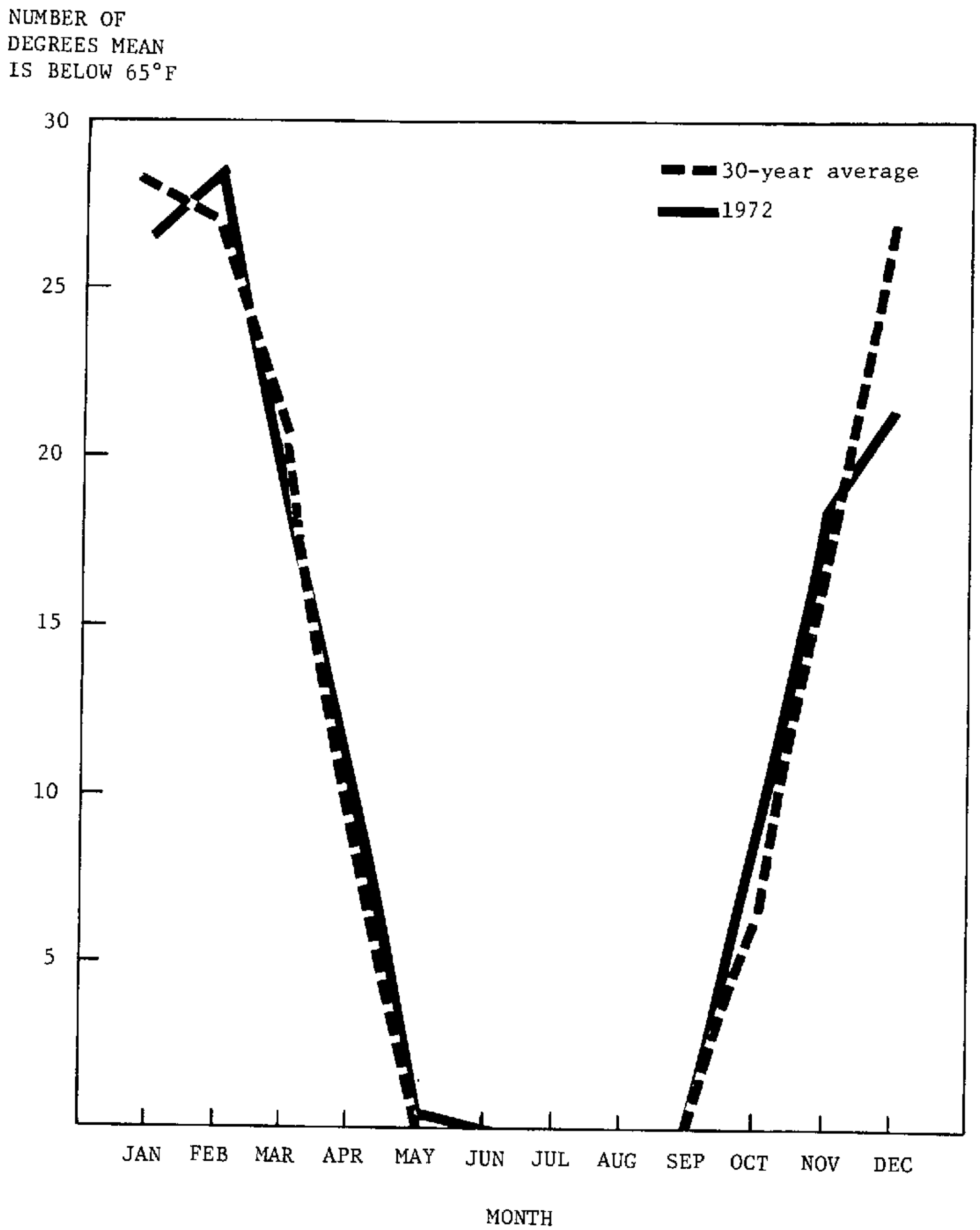


FIGURE 2-5
NEGATIVE DEPARTURE OF MONTHLY MEAN TEMPERATURE FROM 65°F

Because of the variation in point source emissions from month to month, it was necessary to create several different emission files for input to the main modeling program.

In many cases the UTM coordinates or stack parameters were not included in the NEDS file. Supplementary data were readily available from the DC Air and Water Pollution Control Office for point sources located in Washington and were used to complete the NEDS data. Similar data would have been more difficult to obtain for Virginia and Maryland point sources. It was felt that using estimates for this information rather than actual data would not cause any significant difference in the results produced by the model. Consequently, MITRE's best estimates were prepared and used to complete the Virginia and Maryland point source data required by SCIM.

Because the stack parameters for point source were specified in feet and °F, and the model required that the input be in meters and °K, a short computer program was written to convert the values and punch data cards in the format required by the model.

2.7 Selection of Receptors and Grids

2.7.1 Carbon Monoxide Model

The carbon monoxide model was received from Stanford Research Institute along with some of the data that they had used when exercising the model for Washington, D.C. Their grid which has its origin in Virginia, southwest of Washington, was perfectly suited to MITRE's modeling requirements and was therefore used without alteration. One hundred numbers on the grid represent one mile.

As many as 625 receptor points can be specified in the carbon monoxide model. The first locations chosen as receptor points were those sites which continually monitor carbon monoxide. Next, points were selected at two-mile (3.2km) intervals, beginning at the origin of the grid. In the east-west direction the points covered 34 miles (54.5km), while in the north-south direction they covered 22 miles (35.2km).

Upon review of some of the initial results, it was felt that the resolution needed to be improved. Additional receptor points were added at one-mile (1.6km) intervals for the area inside the beltway. This brought the total number of receptor points up to 474.

2.7.2 Sulfur Dioxide Model

This model was designed to use grid coordinates based on the UTM system, and provides for the use of up to three grids, each with its own location, dimensions, area source heights, and mesh size. The size of each grid is limited by the size and number of area sources which can be input. Based on these restrictions one grid of 45 by 42 kilometers was chosen. In the east-west direction, the grid starts at 300 UTM and extends to 345 UTM; in the north-south direction, the grid begins at 4293 UTM and continues until 4335 UTM.

Receptor coordinates used by this model must be expressed in kilometers. In order to make the receptor points approximately compatible with those used in the carbon monoxide model, receptors were specified at three kilometer intervals. In addition, the locations of sites continually monitoring sulfur dioxide were also specified as receptors.

As in the case of the carbon monoxide model, after review of initial results, more receptor points were added to improve the resolution. The additional receptors were positioned every kilometer in those areas surrounding receptors with the highest values. It was found that these areas were downwind from the three power plants operating in the Washington area.

The program was designed to handle a maximum of 130 receptor points. In order to have sufficient data to cover the area of interest, between 220 and 300 receptor points were required. Rather than to modify the program, so that it could handle more receptors, for each set of conditions the program was executed twice, or three times if more than 260 receptors were used.

2.8 Model Limitations

2.8.1 Carbon Monoxide Model

When the APRAC-1A model, was designed several assumptions had to be made in order to assure that the model would neither require data not readily available to a model user nor require excessive amounts of computer time. These assumptions do effect the accuracy of the model predictions, and must be recognized when interpreting the model results. Some of the most important of these limitations are presented in this section.

Meteorological observations can be obtained for most large airports in the country from the National Climatic Center. The availability of meteorological observations for locations other than airports is limited. To assure that surface meteorological data would be available for any area to be modeled, the APRAC-1A program assumes that local airport meteorological observations are valid throughout the city being modeled. In reality, we know this not to be the case. Most airports are located at some distance from the center of the city and are not likely to be surrounded by high buildings and large areas of pavement, both of which effect the wind speed, wind direction and temperature. It is also known that meteorological parameters are not uniform over a large city, and in fact can vary within a block because of air currents created around buildings. No provision for use of more than one set of local meteorological data is certainly a limitation of this diffusion model.

Another problem related to the meteorological data used by this model, is that hourly data are used and no consideration is given to meteorological conditions which occurred earlier in the day, or on the previous day. The model assumes that conditions remain constant during the travel of the pollutant between source and receptor. This introduces more error to the predictions, but magnitude of the resulting error is limited by the fact that the sources closest to a receptor, and thus with the shortest travel times, are the major factors in determining the concentration. "The short travel times from these sources minimize the likelihood of substantial change in the meteorological parameters,"[1] and in turn minimize the error.

[1] Ludwig, F. L. et al. "A Practical, Multipurpose Urban Diffusion Model for Carbon Monoxide". September 1970, page 13.

In Section 2.2.1, a description of the carbon monoxide model, the technique used for calculating emissions by segments is explained. While this must be considered a reasonable technique, it does limit the spatial resolution of the model. Because of the small size of the segments used near the receptor, the best spatial resolution is obtained for receptors for close to the sources. "For farther areas the detailed location of individual sources is not very important because diffusion processes during transport intermingle the individual emissions before they reach the receptor."[1]

Finally, we wish to mention that the model cannot handle the case of calm winds without some adjustments. The model uses a minimum wind speed of 1.0 m/sec. SRI has reported overestimation of high concentrations which might be explained by inadequacy in the treatment of conditions, such as calm winds, conducive to high concentrations.[2]

2.8.2 Sulfur Dioxide Model

As in the case of the APRAC-1A program, several assumptions were required in order to design a workable SO_2 model. Nevertheless, these assumptions do effect the accuracy of the model and must be considered "model limitations".

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[1]Ibid, page 7.

[2]Ludwig, F. G. and W. F. Dabberdt. "Evaluation of the APRAC-1A Urban Diffusion Model for Carbon Monoxide". Stanford Research Institute, February 1972, page 108.

The sulfur dioxide model uses hourly local airport meteorological data and assumes those values are valid for the entire area being modeled. In addition, the model considers each one hour period to have a constant wind speed, wind direction, and atmospheric stability class. Both of these assumptions introduce some error into the receptor concentrations predicted by the model, although the magnitude of the resulting error can not be determined at this time.

Early validations of the model showed that it was inappropriate for predicting concentrations for conditions of light wind, that is less than 1.5 m/sec.[1] Consequently, GEOMET revised the model so that it no longer accepts any wind speed less than 2 knots (1.02 m/sec). No provisions have been made for predicting concentrations when the wind speed is less than 2 knots.

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[1]Koch, R. C. et al. "Validation and Sensitivity Analysis of the Gaussian Plume Multiple-Source Urban Diffusion Model." GEOMET, Inc., November 1971, page 89.

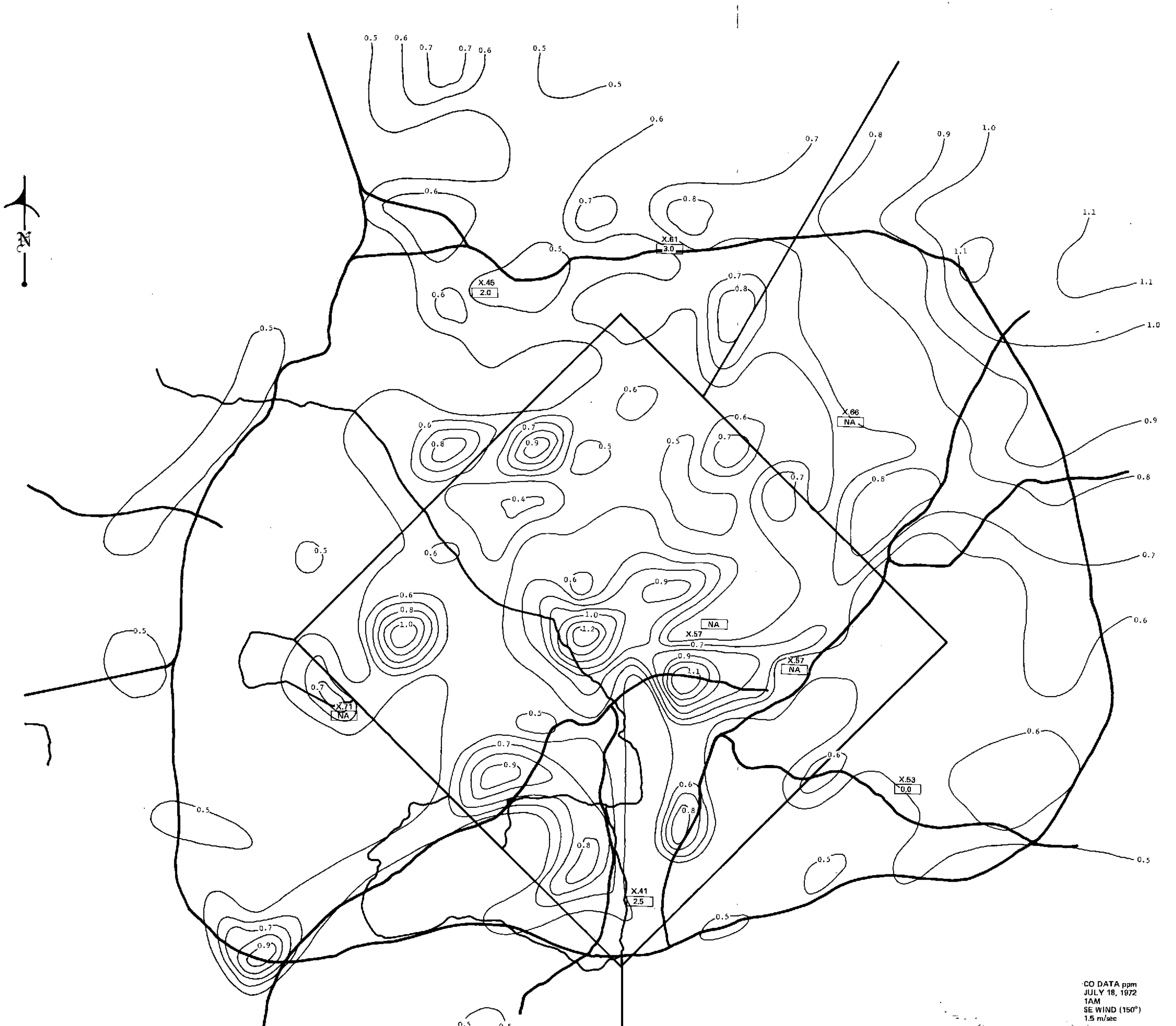
3.0 PRESENTATION AND ANALYSIS OF MODEL RESULTS

3.1 Comparison of Carbon Monoxide Model Results with Measured Air Quality Data

For each of the 14 runs of the carbon monoxide model, the results were plotted and the appropriate isopleths drawn. Figures 3-1 to 3-10 show the maps which were drawn for various hours of the day on July 18, 1972. The maps for 7:00 A.M. on April 24, June 8, September 25 and December 4 appear as Figures 3-11 through 3-14. Each map is identified by the conditions for which the run was made, date, hour of the day, wind speed and direction.

The results of the model were plotted in the same units as reported in the output of the model, that is, in parts per million (ppm). A value of 0.5 ppm is the minimum detectable sensitivity for continuous carbon monoxide instruments. This was chosen as the lower bound for the isopleths drawn. Initially, the isopleths were drawn at 0.5 ppm intervals, which outlined the areas experiencing the highest predicted carbon monoxide values. In order to accentuate those areas and to show the magnitude of change relative to distance covered, isopleths were drawn at 0.1 ppm intervals. In a few cases, isopleths were then drawn for cases less than 0.5 ppm. For the days and hours which were studied, the areas predicted to have the highest carbon monoxide concentrations always appear in the same general locations, although the maximum predicted values do vary considerably. The highest value computed by the model for any of the cases studied, was 3.78 ppm.

In order to compare carbon monoxide values recorded at each of the



CO DATA ppm
JULY 18, 1972
1AM
SE WIND (150°)
1.5 m/sec

X PREDICTED VALUE AT MONITORING SITE
▭ OBSERVED VALUE AT MONITORING SITE

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FIGURE 3-1
PREDICTED CARBON MONOXIDE LEVELS

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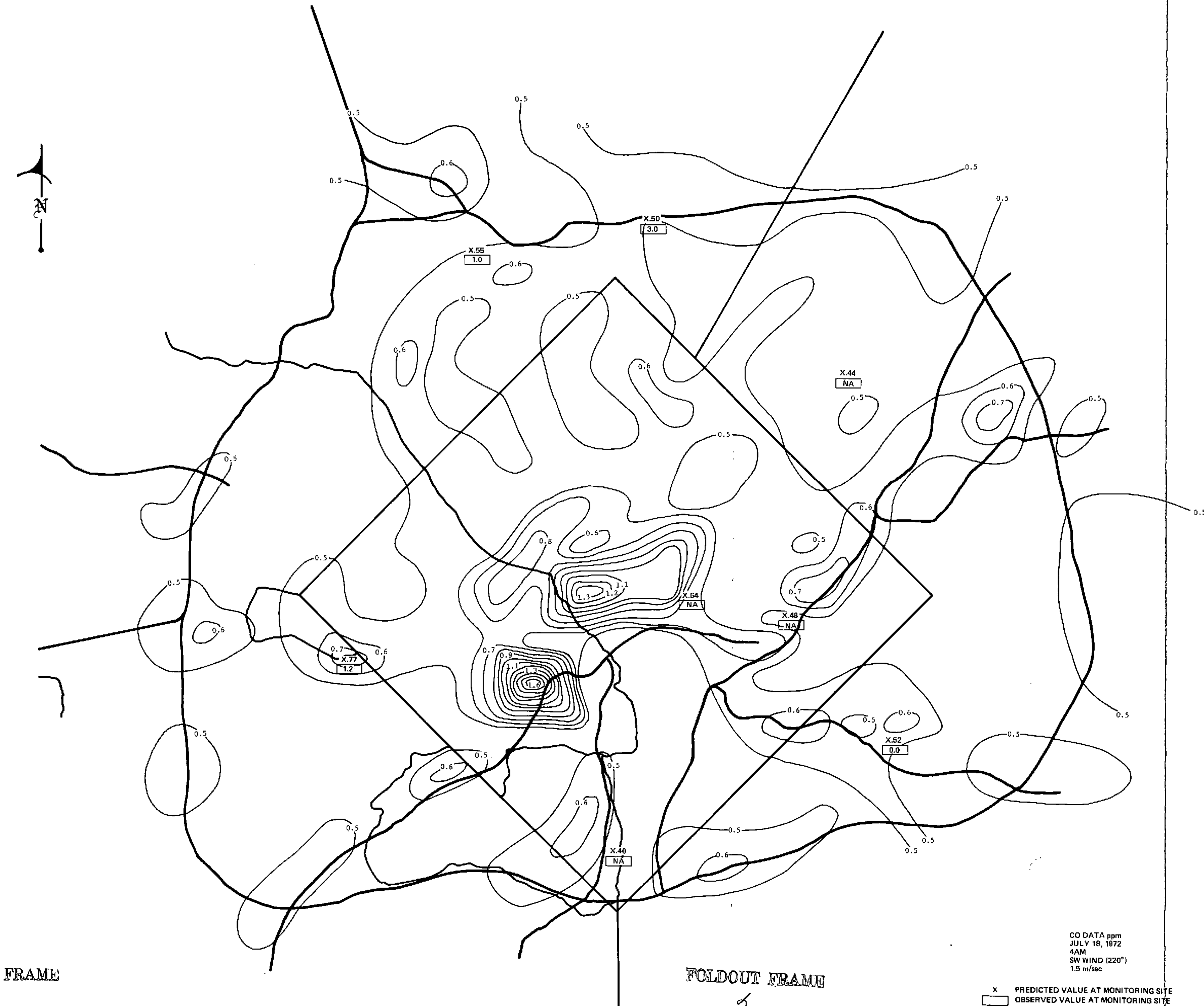

FIGURE 3-2
PREDICTED CARBON MONOXIDE LEVELS

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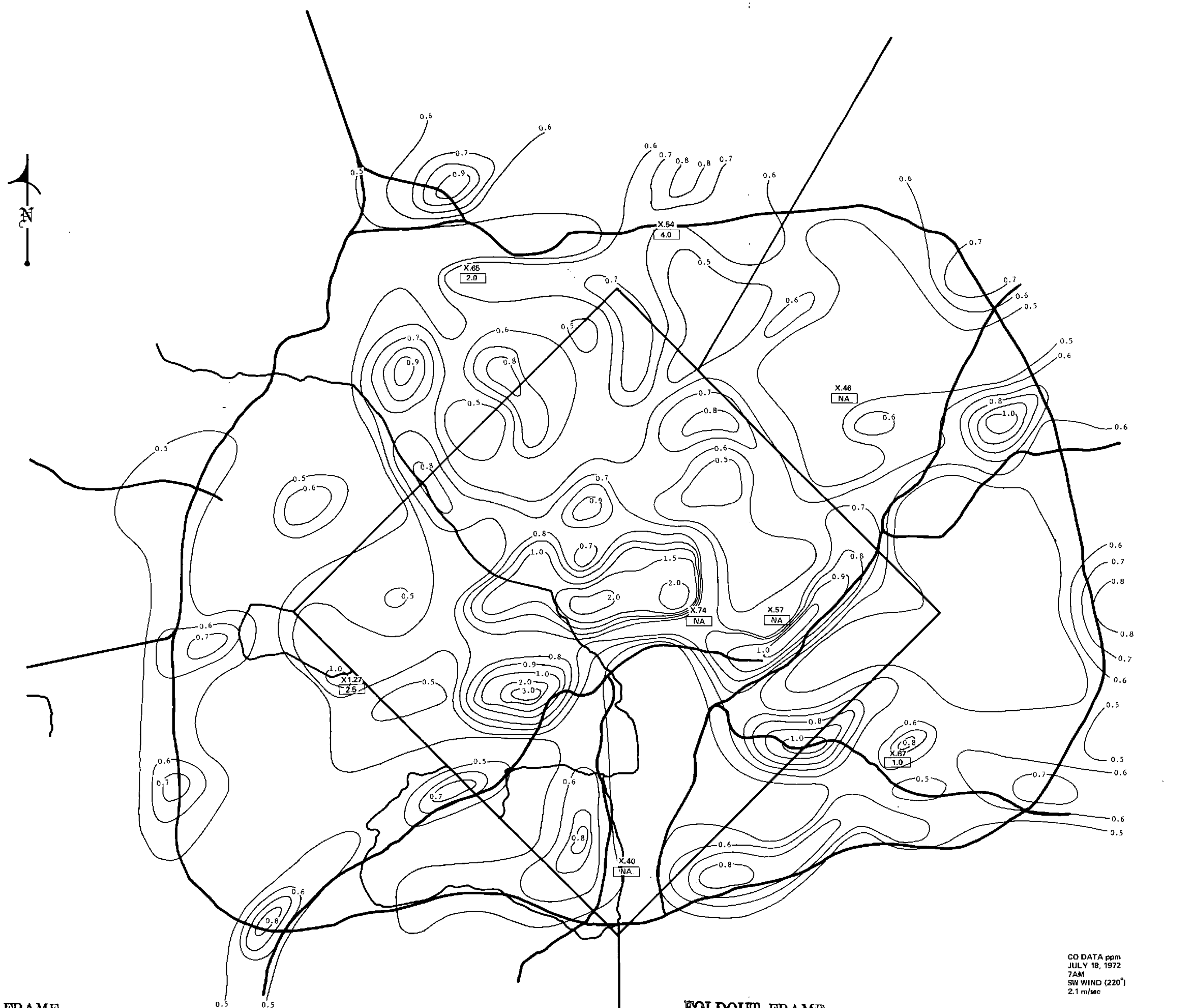

FIGURE 3-3
PREDICTED CARBON MONOXIDE LEVELS

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FIGURE 3-4
PREDICTED CARBON MONOXIDE LEVELS

CO DATA ppm
JULY 18, 1972
10AM
NE WIND (20°)
3.1 m/sec

X PREDICTED VALUE AT MONITORING SITE
▭ OBSERVED VALUE AT MONITORING SITE

FIGURE 3-5
PREDICTED CARBON MONOXIDE LEVELS

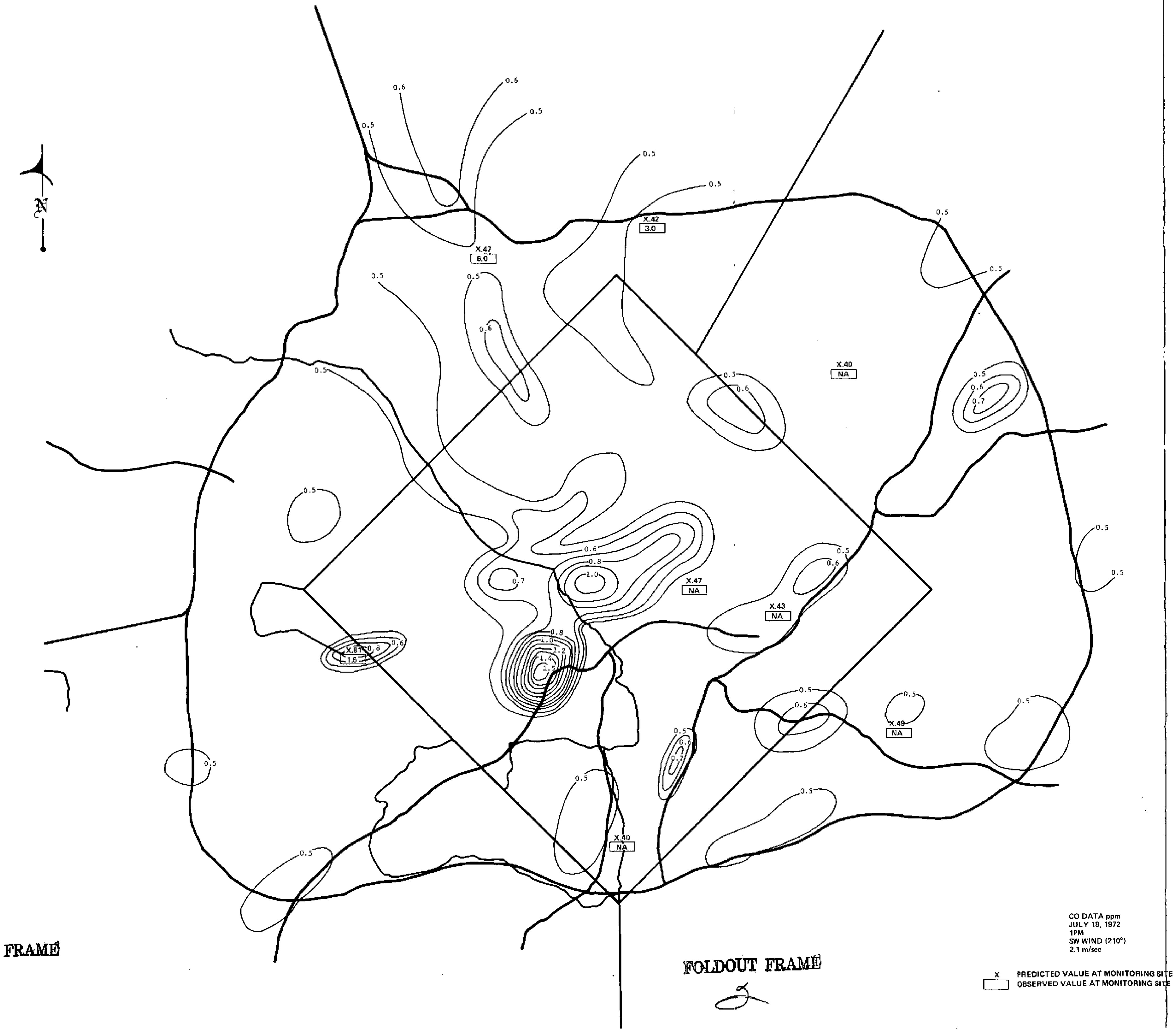

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FIGURE 3-6
PREDICTED CARBON MONOXIDE LEVELS

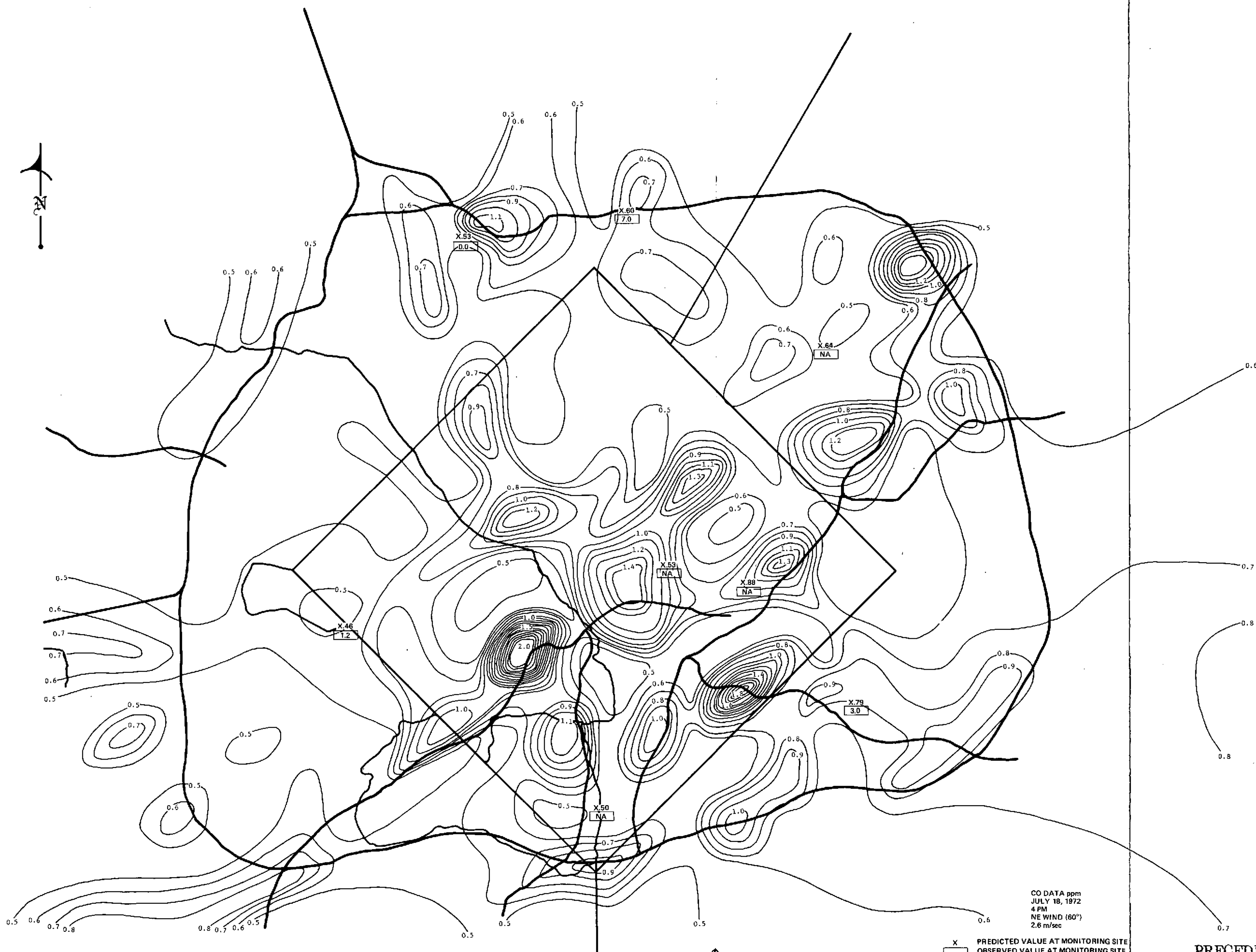

FIGURE 3-7
PREDICTED CARBON MONOXIDE LEVELS

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2
FOLDOUT FRAME

FIGURE 3-8
PREDICTED CARBON MONOXIDE LEVELS

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FIGURE 3-9
PREDICTED CARBON MONOXIDE LEVELS

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2

FIGURE 3-10
PREDICTED CARBON MONOXIDE LEVELS

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FIGURE 3-11
PREDICTED CARBON MONOXIDE LEVELS

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FIGURE 3-12
PREDICTED CARBON MONOXIDE LEVELS

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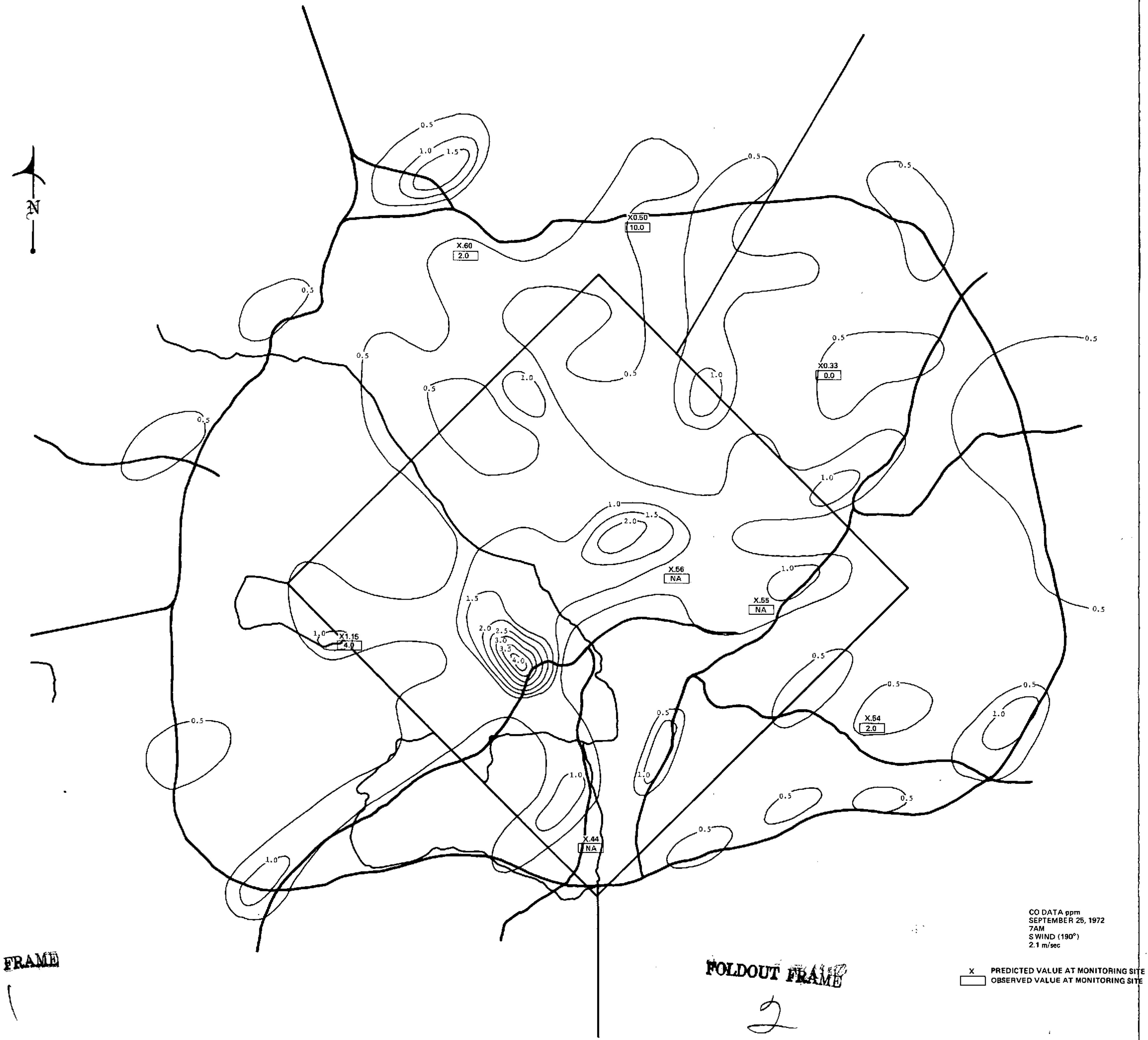

FIGURE 3-13
PREDICTED CARBON MONOXIDE LEVELS

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FIGURE 3-14
PREDICTED CARBON MONOXIDE LEVELS

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continuously monitoring stations to the predicted values, the stations and their recorded values were shown on the maps. One exception is that the values for the Gaithersburg Laboratory do not appear because the laboratory lies beyond the boundaries of the map. All of the CO data which we received for the monitoring stations were reported in parts per million. Of the four stations which reported data on July 18, 1972, three gave their values to the nearest whole ppm and the station at Wards - 7 Corners, Virginia, recorded their values to one decimal place. The model's output values are recorded to two decimal places which is beyond the present capabilities for ambient ground-level samplers. (As mentioned earlier, the threshold of ambient ground-level CO sensors in 0.5 ppm.) These facts can result in a poor correlation between the predicted values and the measured values because of the instruments limitations. To compare the measured and predicted values on the same scale of accuracy, the predicted values should be rounded to the nearest ppm.

This rounding was done for the July 18, 1972 predicted values. The adjusted predicted values were plotted against the recorded values for each station and the results are shown in Figure 3-15. A dotted line has been drawn on each of the four graphs to indicate the set of points that represent perfect agreement between measured carbon monoxide values and the predicted values. For each of the stations, the majority of the July 18 points plotted do not lie along the dotted line. Based on the data used to prepare these graphs, we find that 8 points (22%) lie on the dotted line and only 3 points (8%) lie below the lines.

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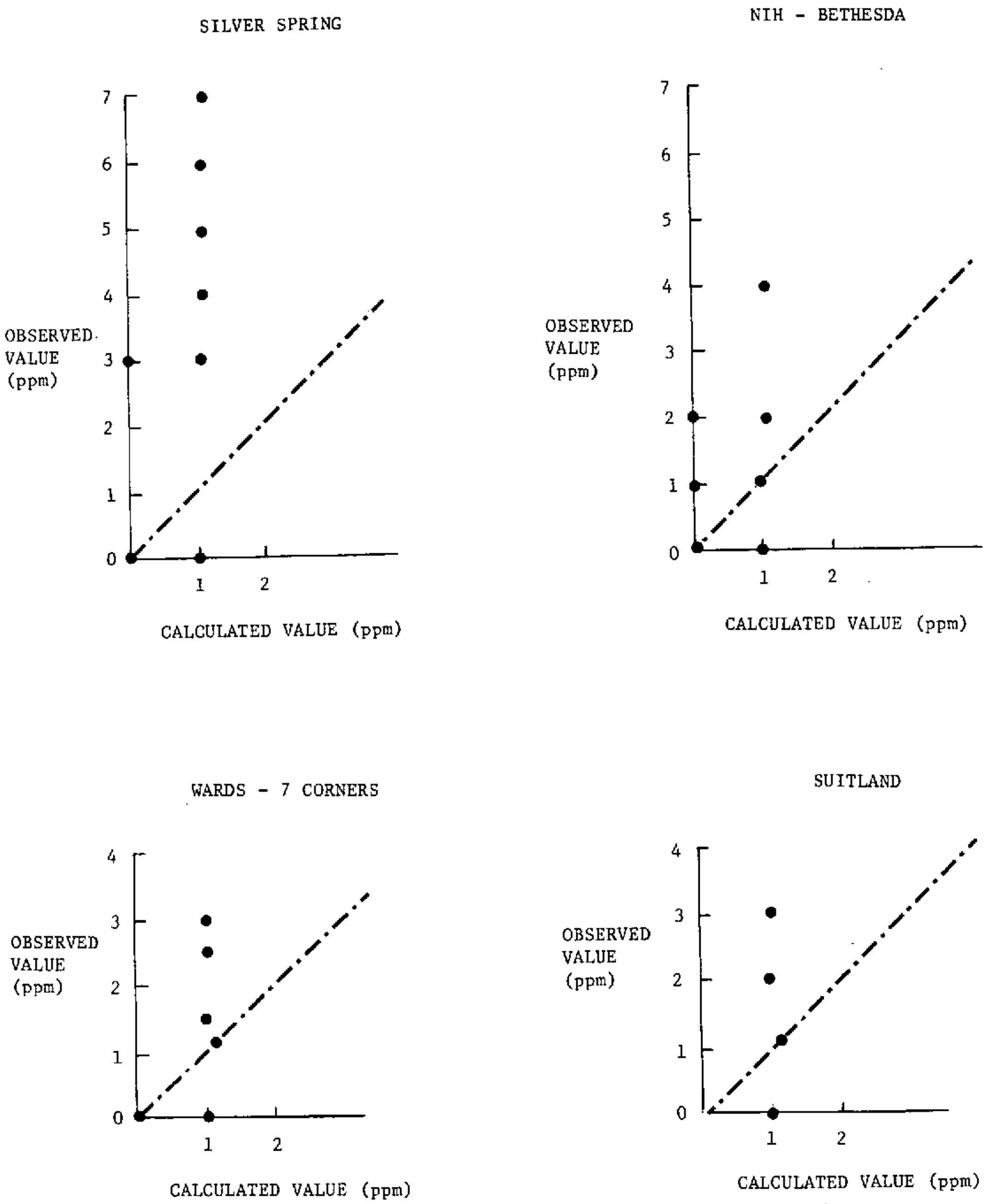

Note: broken line represents perfect agreement.

FIGURE 3-15
CO CALCULATED VALUES VERSUS MEASURED VALUES
JULY 18, 1972

This indicates that 70% of the time, the model was predicting values which were too low. In one of the APRAC documents[1], the following statement is made, "The model generally underestimates concentrations below 7 or 8 ppm and overestimates those at the higher values." This is exactly the situation on July 18 because the highest value recorded at any of the stations for the hours of our study was 7 ppm.

Although rounding the predicted values to the nearest ppm is useful for comparison to the measured values, we must consider the values as they were predicted by the model in order to determine the type of error which is occurring. The rounding technique makes it possible to determine if the error is due to the instrument accuracy limitation of 1 ppm, but if that proves not to be the case, it is impossible to determine what type of function represents the error. In this case, review of the unadjusted predicted values showed that the function was neither constant nor exponential.

Reasons for the variation between the predicted and measured values are related to the limitations of the model and characteristics of the sampling stations. Discussion of sources of error within the model has been covered in the previous Section 2.8, Model Limitations, so we will now turn to sources of error related to the sampling stations.

Several characteristics of the sampling site could also be the reason for the discrepancy between the measured data and the predicted

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[1]Ludwig, F. L. and W. F. Dabberdt. "Evaluation of the APRAC-1A Urban Diffusion Model for Carbon Monoxide", Stanford Research Institute, February 1972, Page 108.

values. The two most important of these characteristics are the site and sampling manifold locations. Air quality measurements are greatly affected by the immediate surroundings to the intake probe. The EPA states that "the surrounding area should be free from stacks, chimneys, or other local emission points".[1] Building aerodynamics can also cause unreliable air quality values to be recorded. "The probe should not be located on the face of the building downwind of the prevailing wind direction to avoid the transport of contaminants from ground level by backflow in the building wake. Similarly, the south face of the building should be avoided so that convection currents will not carry pollutants up from the ground level."[2] Height of the sampler also influences the data values recorded. One study[3] done in Nashville, Tennessee showed the degree to which carbon monoxide concentrations varied with height of the sampler. During one morning rush hour on a day in November, a carbon monoxide value of 25.5 ppm was recorded at a height of about 8 feet, while a value of about 14 ppm was measured at an elevation of 110 feet. Earlier in the day, between 5 and 6 A.M. before rush hour

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[1] Environmental Protection Agency, Office of Air Programs. "Guidelines: Air Quality Surveillance Network". AP-98. May 1971, Page 14.

[2] Golden, J. and T. R. Morgan. "Designing an Air Monitoring Facility", MITRE Corporation, August 1970, Page 23.

[3] Schnelle, K. B. Jr. et al. "A Study of the Vertical Distribution of Carbon Monoxide and Temperature Above an Urban Intersection", Presented at the APCA National Meeting, 1969, New York City, Paper Number 69-152.

traffic began, the variation was much less. At 8 feet, about 4.2 ppm were recorded, at 20 feet approximately 3 ppm were recorded, and at 110 feet, the value recorded increased to 4.5 ppm.

All these factors relating to the location of the site and the sampling manifold, as well as factors such as the maintenance of the equipment and frequency of calibration must be kept in mind when using air quality data measured by ground sensors. Although measured air quality values are representative of the overall pollutant level in the vicinity of the sampler, they actually are only a measure of the pollutant concentration at the exact position of the sampling manifold.

As mentioned earlier, the carbon monoxide model is only capable of computing at best, one value for every 125 meters. Consequently, a direct correspondence between the predicted values and the measured values should not be expected, because one is comparing a value at one point with a value predicted over a pie shaped area of 125 meters in length. Therefore any distance less than one hundred meters would be in excess of the resolution of the model. Nevertheless, it would be quite useful to study and revise the model input data and the model in order to improve the correlation of the measured values and the predicted values.

3.2 Comparison of Sulfur Dioxide Model Results with Measured Air Quality Data

The results of the 14 cases for which the sulfur dioxide model was run, were plotted on the receptor grid. The appropriate isopleths were drawn for each case and the resulting maps are shown in Figures 3-16 to 3-29. The first ten maps are for the various hours of July 18, 1972, and the next four maps represent the 7 A.M. isopleths predicted for April 24, June 8, September 25, and December 4. Each map is identified by the conditions for which the run was made, date, hour of the day, wind speed and direction.

The output of the model is in units of micrograms per cubic meter ($\mu g/m^3$), so this unit was used for the data plotted on the maps. The minimum detectable sensitivity for continuous sulfur dioxide instruments is 26 $\mu g/m^3$, which was considered as the lowest value for which an isopleth would be drawn. Review of the maps revealed there would be no significant difference between the shape of a 26 $\mu g/m^3$ isopleth and a 50 $\mu g/m^3$ isopleth, so 50 $\mu g/m^3$ isopleth was the lowest value line drawn. Continuous SO_2 instruments are specified to measure to the nearest 0.02 ppm, which is equal to approximately 53 $\mu g/m^3$. Initially, the isopleths were drawn at 50 $\mu g/m^3$ intervals which proved to provide patterns of satisfactory detail without overcrowding the maps. Only in a few cases where the predicted values dropped sharply over a short distance was it necessary to draw isopleths at 100 $\mu g/m^3$ intervals rather than 50 $\mu g/m^3$ intervals.

Three areas of high concentrations appeared on every map although their location changed considerably. It was found that each area

1

2

FIGURE 3-16
PREDICTED SULFUR DIOXIDE LEVELS

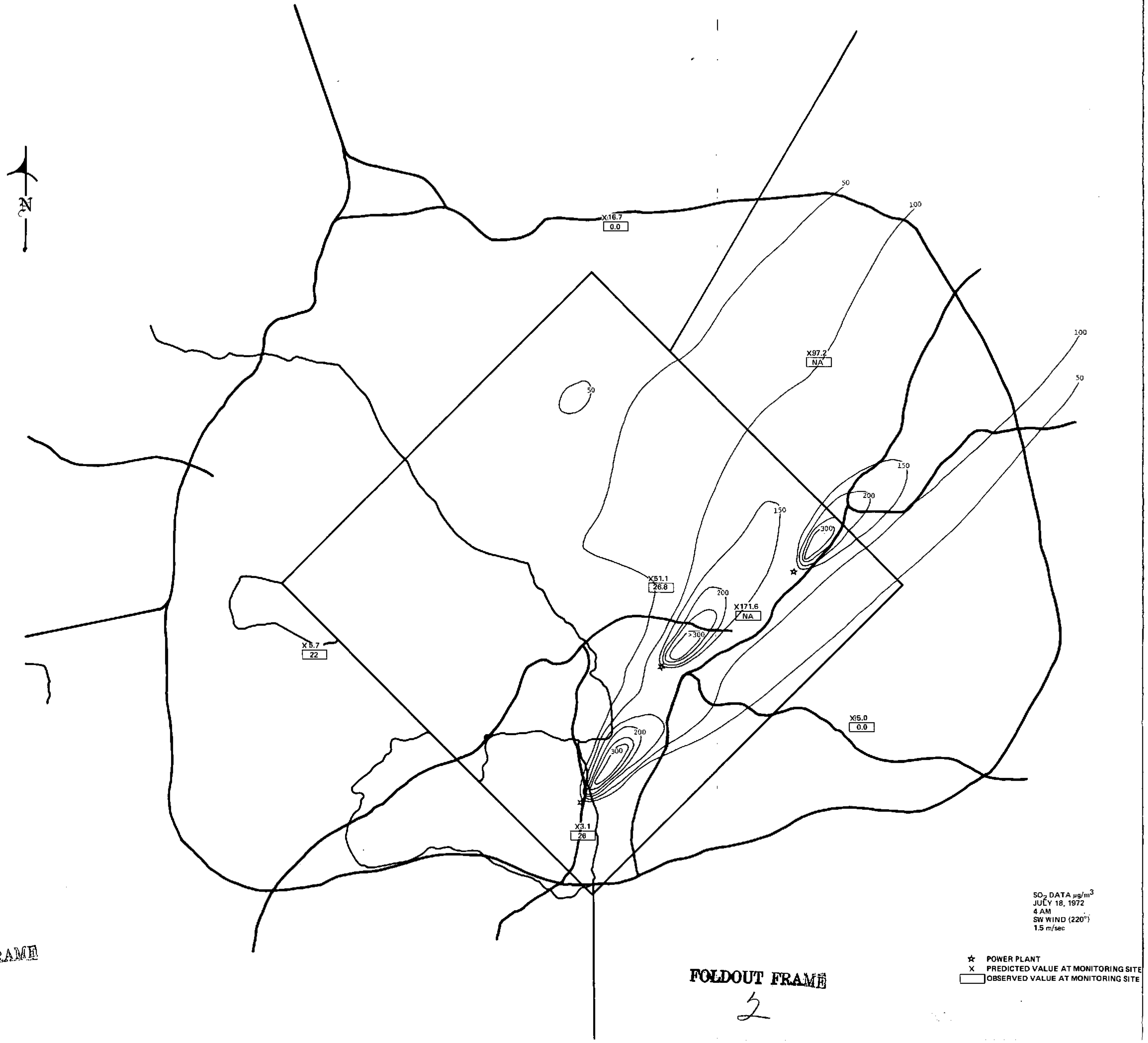

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FIGURE 3-17
PREDICTED SULFUR DIOXIDE LEVELS

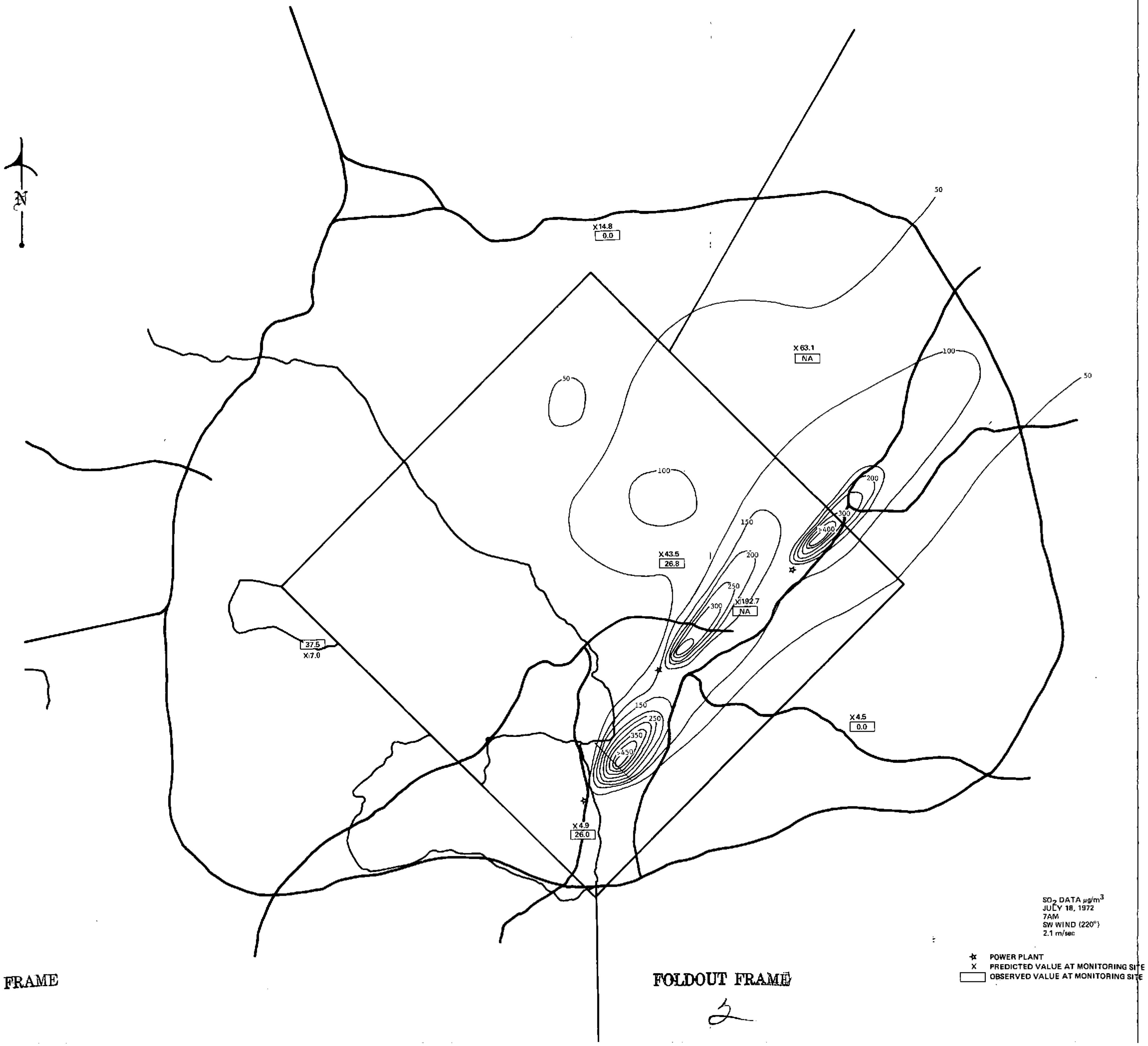

FIGURE 3-18
PREDICTED SULFUR DIOXIDE LEVELS

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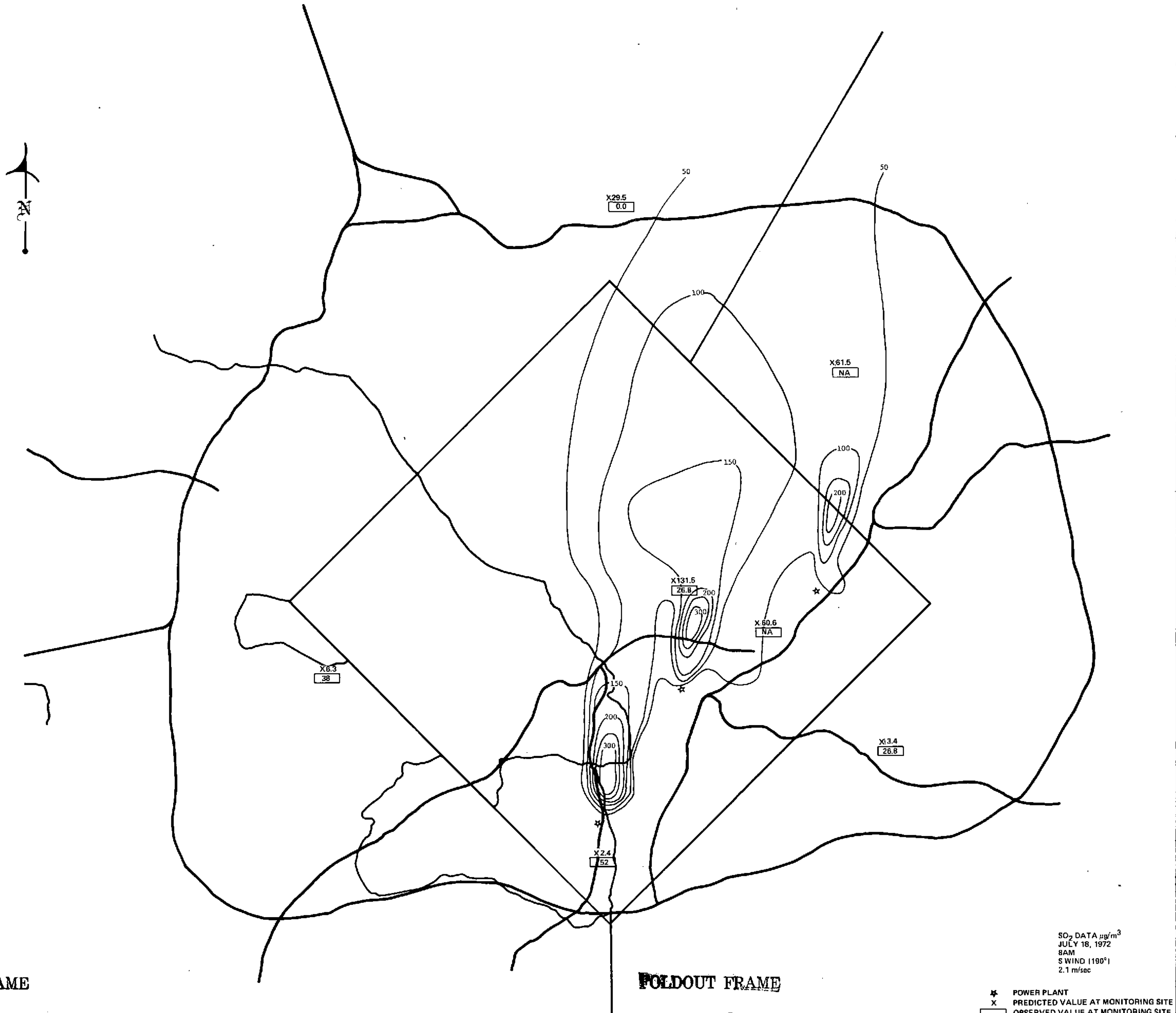

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FIGURE 3-19
PREDICTED SULFUR DIOXIDE LEVELS

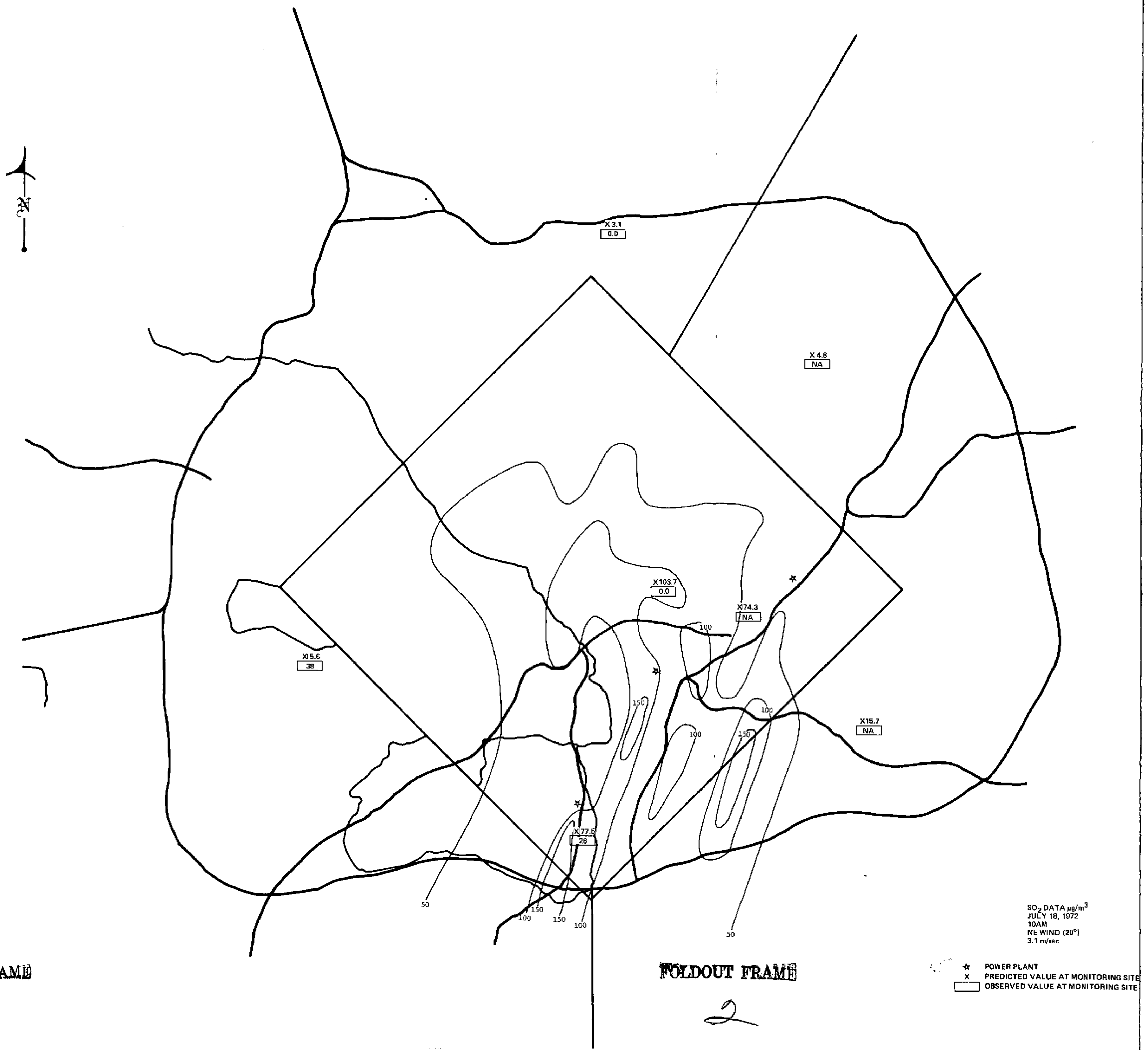

FIGURE 3-20
PREDICTED SULFUR DIOXIDE LEVELS

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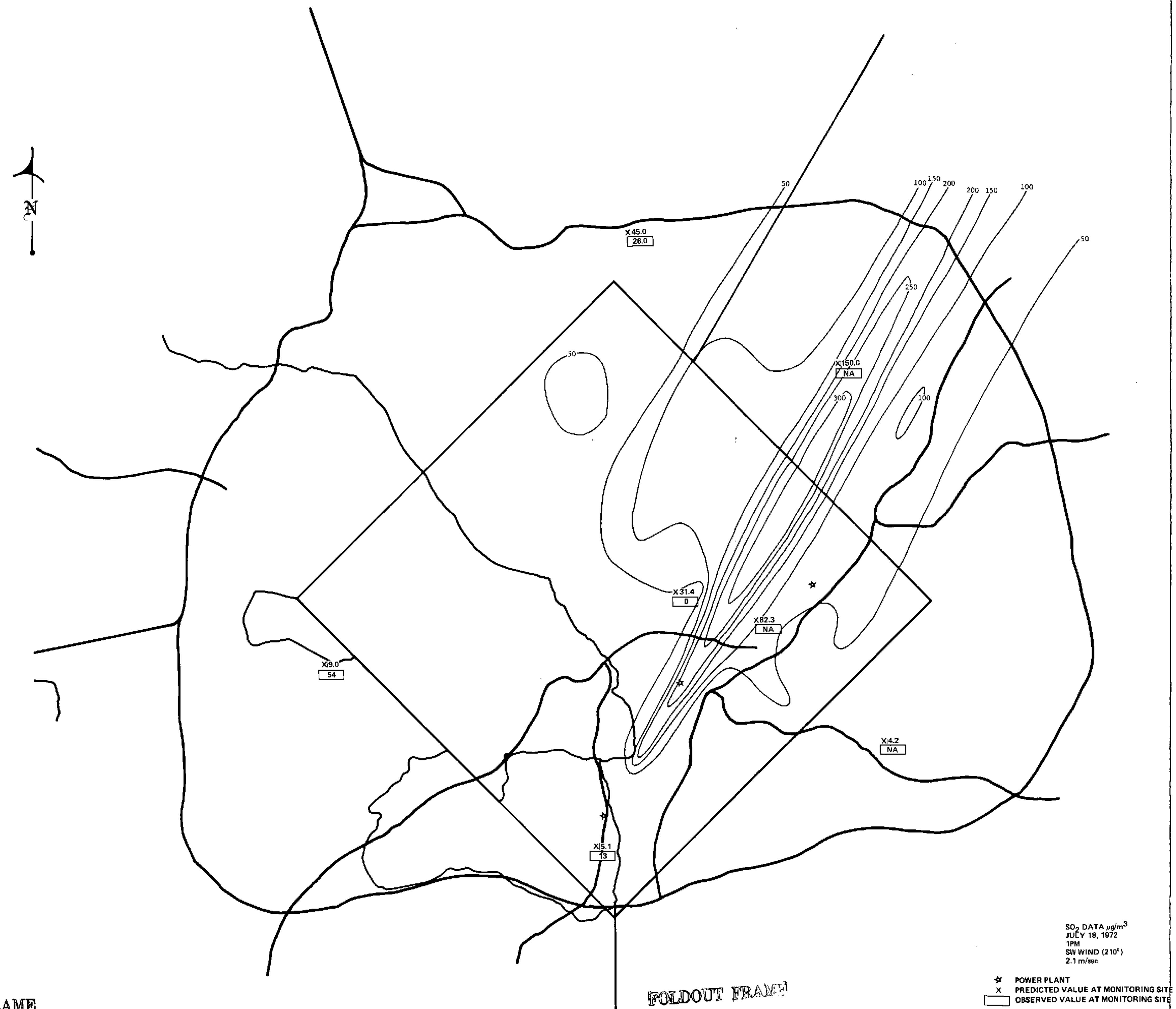

FIGURE 3-21
PREDICTED SULFUR DIOXIDE LEVELS

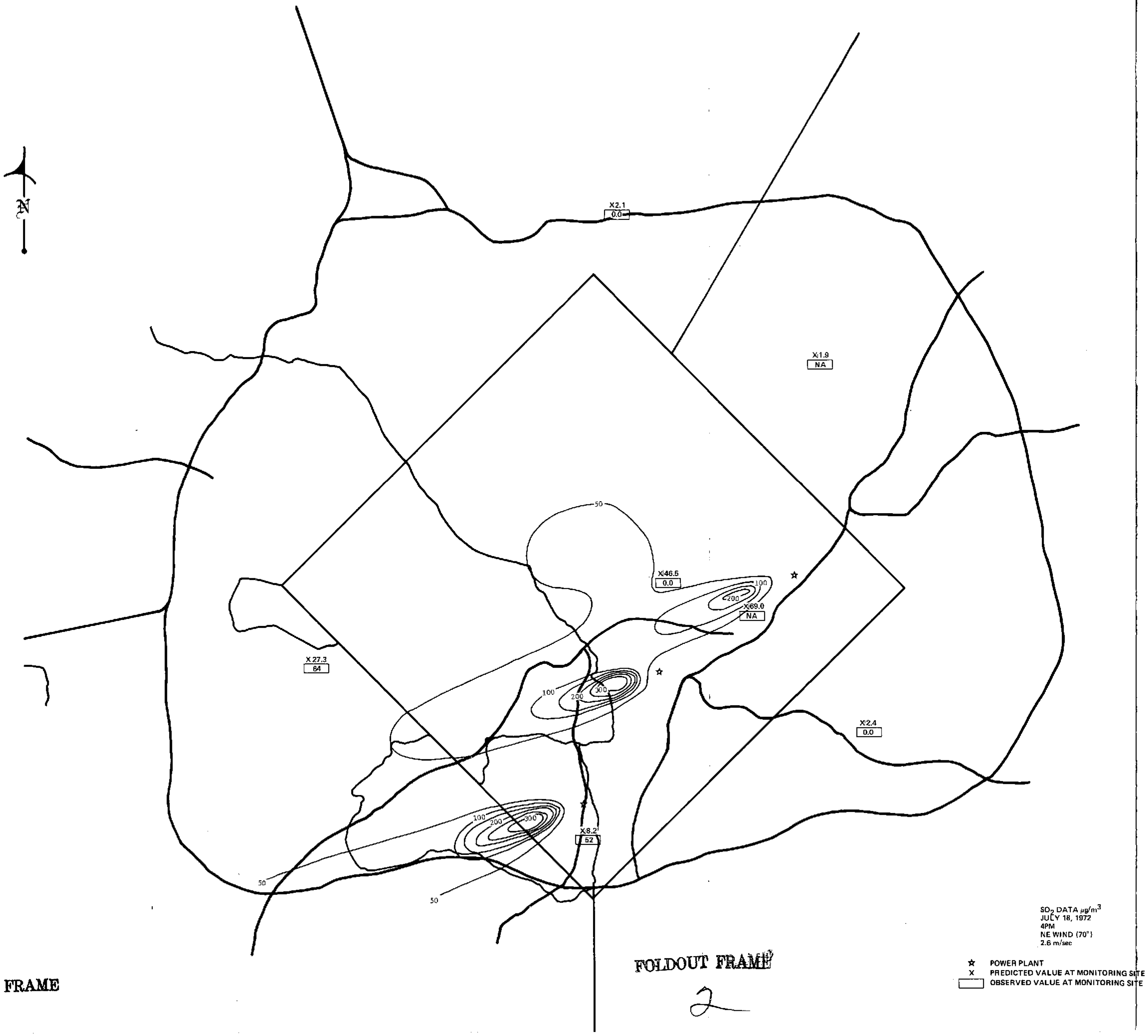

FIGURE 3-22
PREDICTED SULFUR DIOXIDE LEVELS

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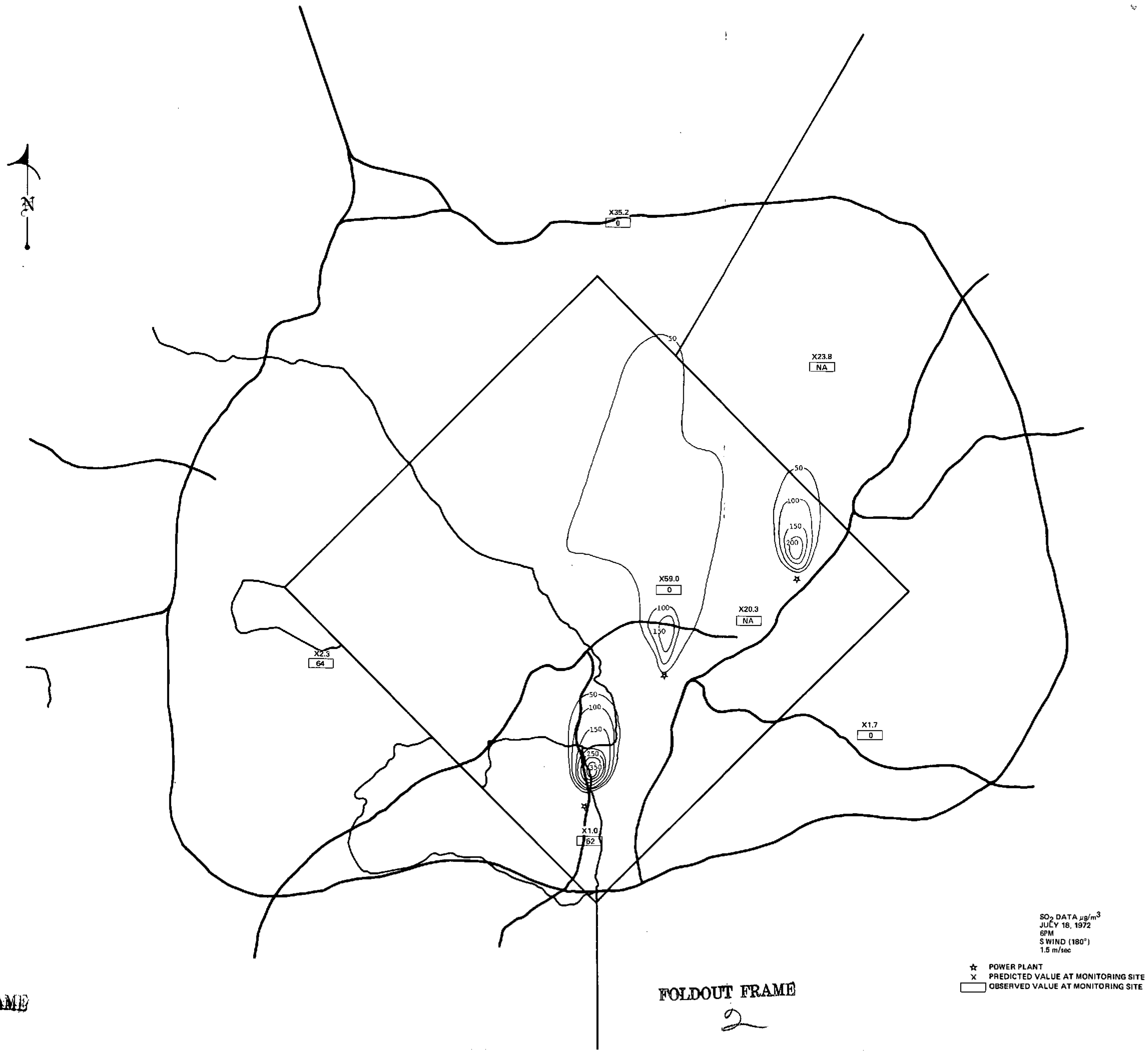

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FIGURE 3-23
PREDICTED SULFUR DIOXIDE LEVELS

FIGURE 3-24
PREDICTED SULFUR DIOXIDE LEVELS

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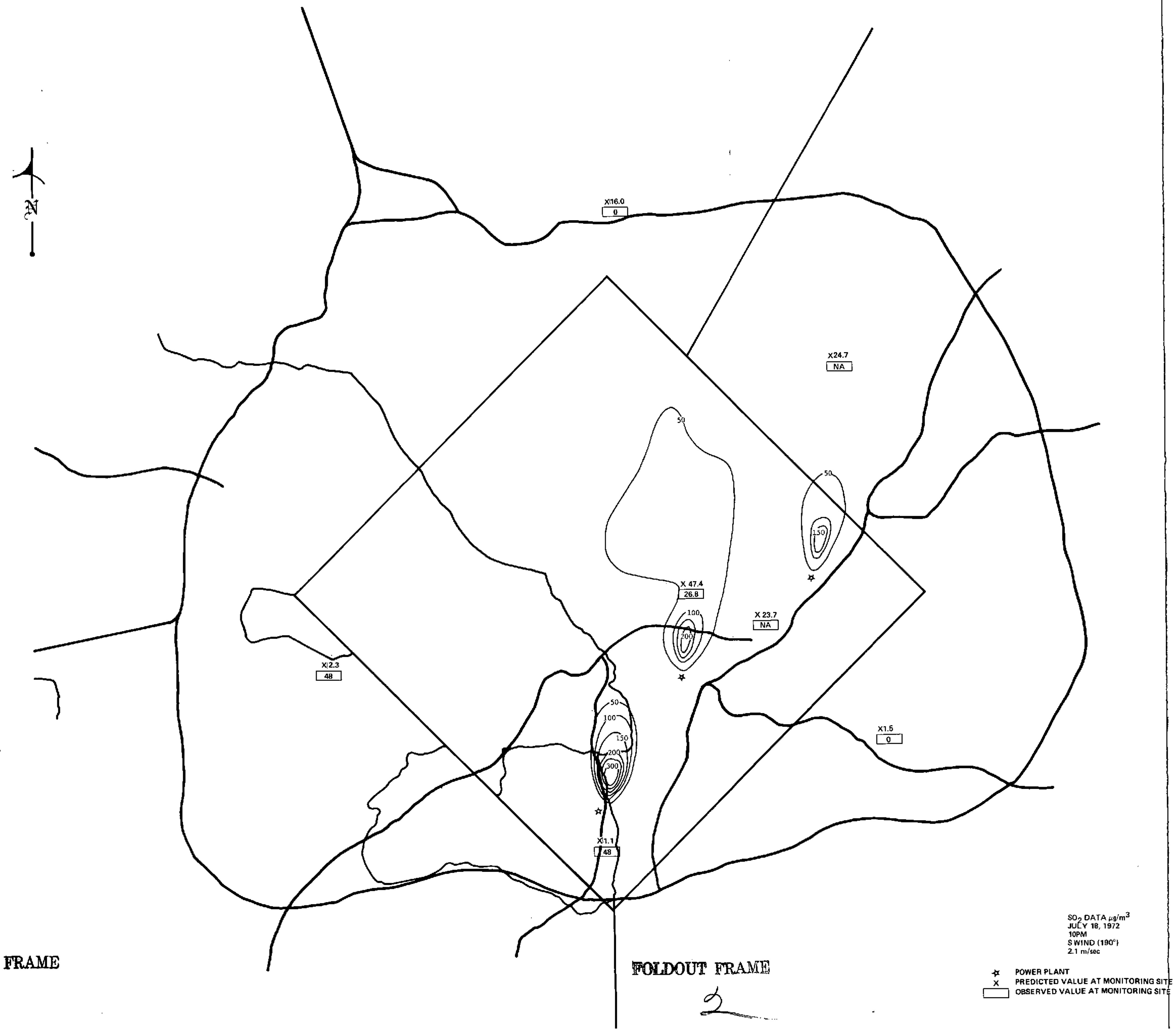

FIGURE 3-25
PREDICTED SULFUR DIOXIDE LEVELS

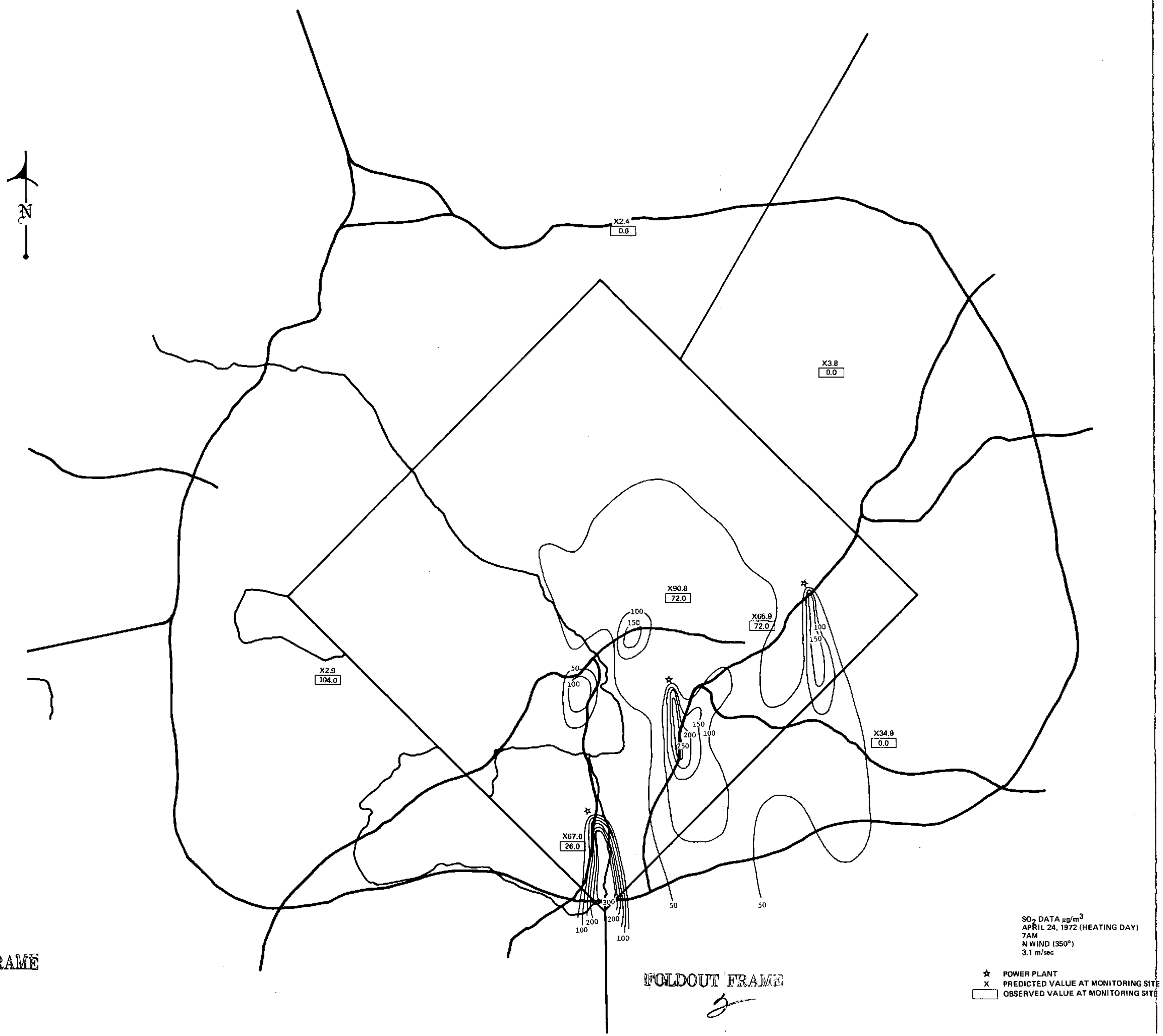

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FIGURE 3-26
PREDICTED SULFUR DIOXIDE LEVELS

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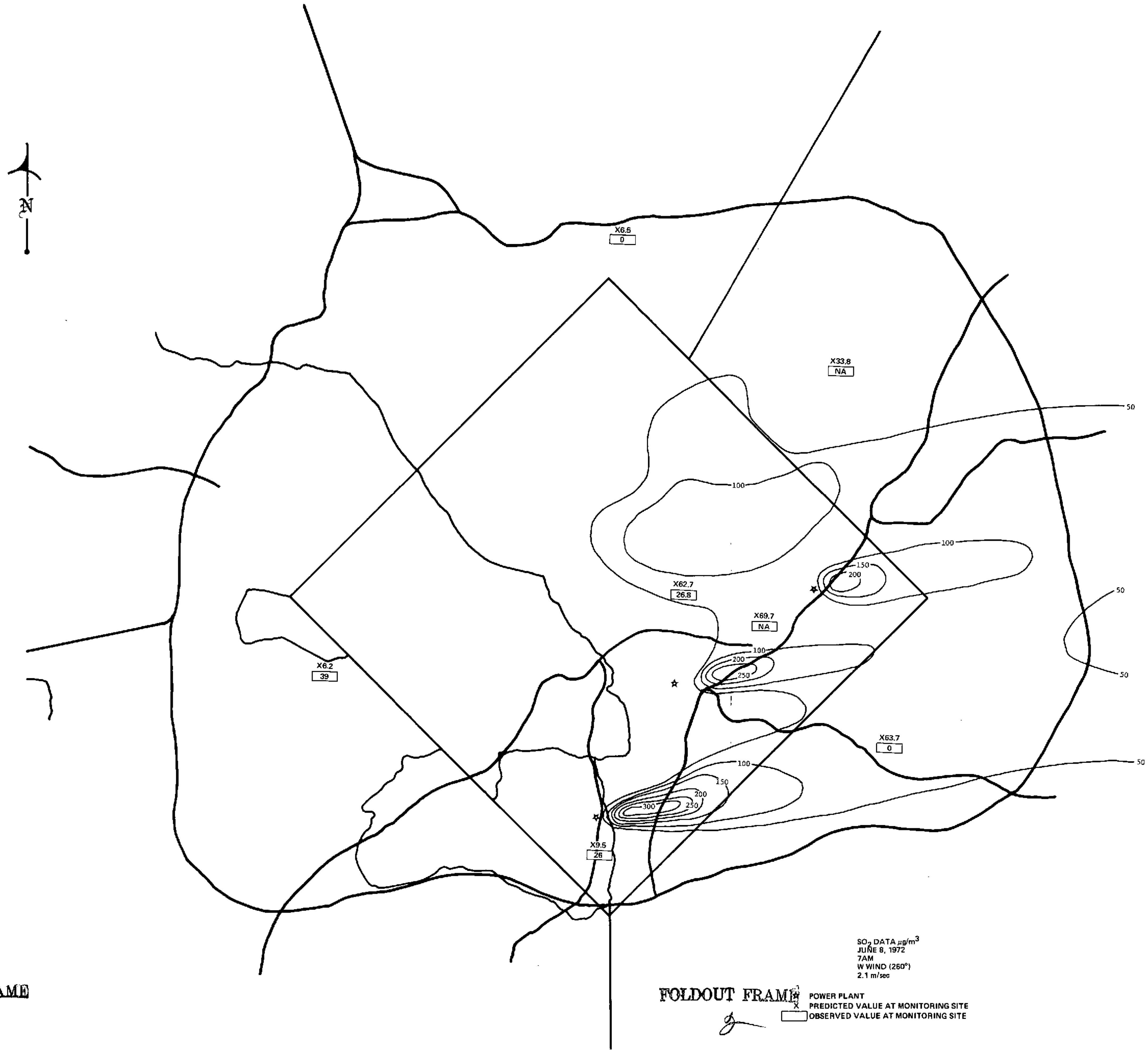

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FIGURE 3-27
PREDICTED SULFUR DIOXIDE LEVELS

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FOLDOUT FRAME 2

FIGURE 3-28
PREDICTED SULFUR DIOXIDE LEVELS

SO_2 DATA $\mu g/m^3$
DECEMBER 4, 1972 (HEATING DAY)
7AM
NE WIND (70°)
2.6 m/sec

☆ POWER PLANT
X PREDICTED VALUE AT MONITORING SITE
▭ OBSERVED VALUE AT MONITORING SITE

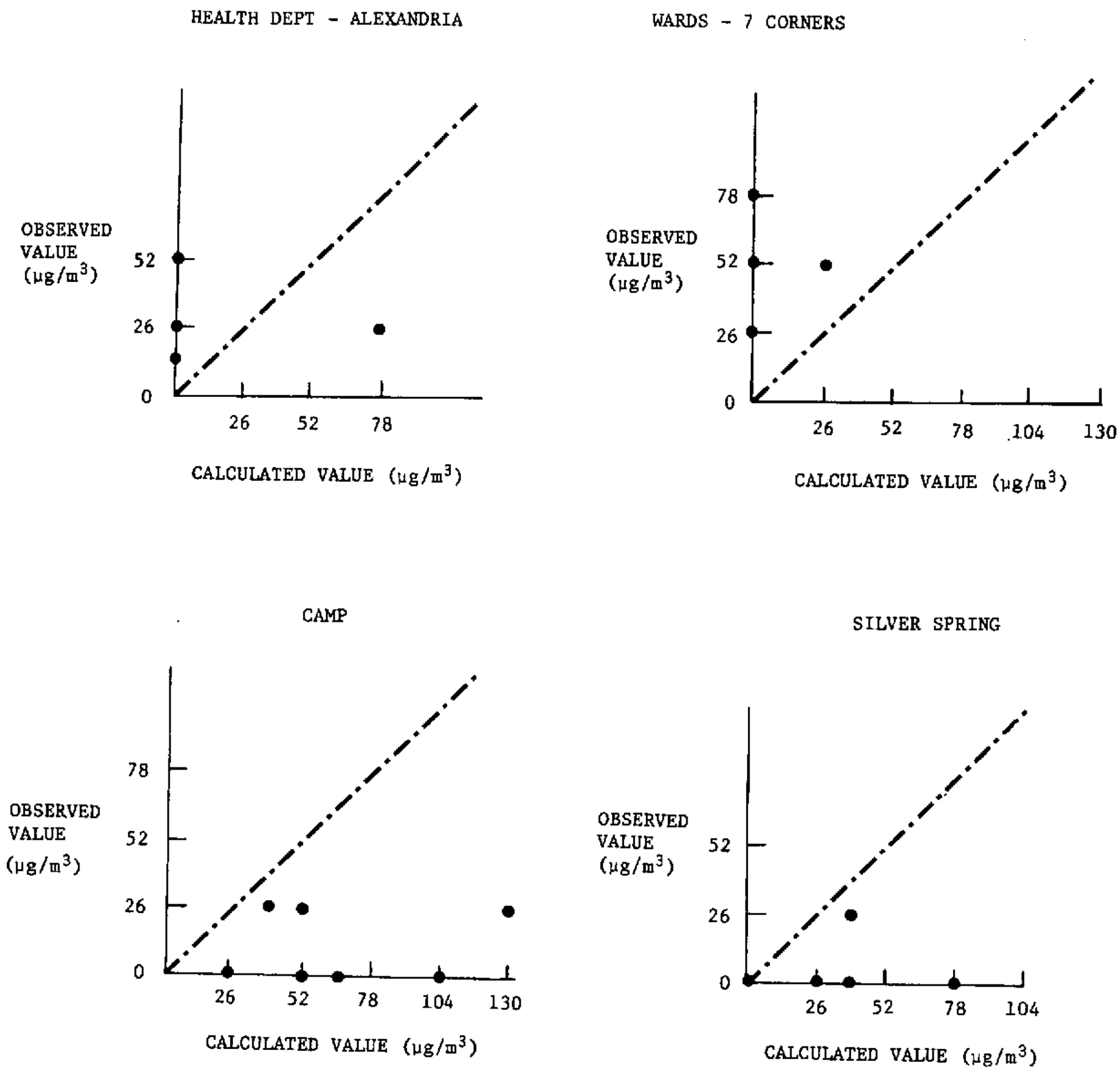
FIGURE 3.29
PREDICTED SULFUR DIOXIDE LEVELS

always appeared downwind from the location of one of the power plants operating within the grid. The location of these power plants has been noted on each map. The highest value computed by the model for any case studied was 953.3 $\mu g/m^3$ or approximately one half a projected one hour standard based on the EPA three hour standard of 1300 $\mu g/m^3$.

The continuously monitoring sulfur dioxide stations and their recorded values were shown on the maps for comparison with the predicted values. Those data which were provided to MITRE in units of ppm were converted to $\mu g/m^3$ by multiplying by a factor of 2681, so that all measured data noted on the maps is in units of $\mu g/m^3$.

Most of the sampling stations reported their data to the nearest 0.01 ppm (26.8 $\mu g/m^3$), but the Wards - 7 Corners site recorded their values to the nearest thousandth of a ppm (13 $\mu g/m^3$). The model's results were calculated to the nearest tenth of a $\mu g/m^3$ which is considerably beyond the accuracy of the ground sensors. In order to compare the measured and the predicted values on the same scale of accuracy, the predicted values were rounded to the nearest 13 ppm.

The adjusted values which were predicted for July 18, 1972 were plotted against the recorded values for each station on the same date. The results for four of the stations are presented in Figure 3-30. Data were available for a fifth station, but were inconclusive because only one value greater than zero was reported, and all the predicted values were zero. On the four graphs shown, a dotted line has been drawn to indicate the set of points representing perfect agreement between the



Note: broken line represents perfect agreement.

FIGURE 3-30
SO_2 CALCULATED VALUES VERSUS MEASURED VALUES
JULY 18, 1972

measured sulfur dioxide values and the predicted values. Except for one point at the origin on the Silver Spring graph, none of the points lie along the dotted lines. Based on the data used to prepare these graphs, it was calculated that 44% of the points lie below the line and that 56% of the points lie above the line. Based on this sample we find that the model tends neither to consistently overpredict nor underpredict the values measured at ground level. Looking again at Figure 3-30 and considering the data for each site separately, we find that for the CAMP station and the Silver Spring station the model always overpredicted. In all except one case the model underpredicted the SO_2 concentrations for the Alexandria and 7-Corners, Virginia, locations. This may indicate that the variations between the measured and the predicted values are as much a function of the receptor location as of the model accuracy. It is possible that a larger data sample would show an overall consistent trend, but it is also possible that some variable or combination of variables would have to be held constant in order for the data to show such a trend. GEOMET has also found the model to give both overpredictions and underpredictions for short term concentrations. One variable which has been found to affect the predictions is wind speed. As the wind speed decreases, the trend shifts from underpredicting to overpredicting.[1] Thus far, this is the

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[1] Koch, Robert C. et. al. "Validation and Sensitivity Analysis of the Gaussian Plume Multiple-Source Urban Diffusion Model". November 1971, Page 91.

only related factor to be identified, so it has been concluded that "The prediction errors appear to result from a variety and random sequence of errors in both the observations and the model parameters."[1]

The discussion of problems related to the recorded observations which appeared in the previous Section (3.1) on the carbon monoxide model results, also applies here. Location of the sampling station and its intake probe, frequency of calibration, frequency of equipment maintenance, are all factors which can introduce error into the measured values. Discussion of sources of error within the model has been covered in the previous Section 2.8, Model Limitations. One of the things mentioned in that section, was that this sulfur dioxide model is only capable of computing at best, one value for approximately every 80 meters. As long as we are comparing a value measured at one specific location with a value predicted over an 80 meter distance, there is an upper-bound on the correlation which can be achieved. A better understanding of what factors are causing discrepancies between the measured and the predicted values and ways to improve the correlation, can only result from additional work with the model.

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[1]Ibid. Page 93.

4.0 ANALYSIS OF AIRBORNE SENSORS

The selection of those airborne sensors to be analyzed in detail for suitability on the aircraft air quality monitoring system was made by NASA/LRC personnel. The experiments initially suggested for study included the following:

High Speed Interferometer (HSI)

Lower Atmosphere Composition and Temperature Experiment (LACATE)

Monitoring Air Pollution from a Satellite (MAPS)

Laser Radar (LIDAR)

Multi-Pollutant COPE (CIMATS)

In-Situ Sampling (Grab Sampler)

As the analysis proceeded it became apparent that some of the experiments listed above were not as well suited for inclusion in the air quality monitoring system as was first expected. For this reason the depth of the analysis of the grab sampler experiment being developed at Langley Research Center was reduced. It was considered more appropriate and of greater value to include an analysis of the airborne air quality contact sensor system used by the Environmental Protection Agency in the Los Angeles Regional Pollution Project (LARPP).

Futhermore, during the analysis several other systems had been identified which had sufficient merit to warrant inclusion in this study. Among these were the following:

Differential Absorption Remote Sensing (DARS)

Langley Gas Filter Correlation Instrument for CO (LGFCI)

Langley Modified Gas Filter Correlation Instrument for SO_2 (MOD. LGFCI)

In total, seven classes of instruments were analyzed and documented (see Section 4.2). Table 4-1 presents a summary of the characteristics of the various remote sensors discussed below.

4.1 Sources of Information

The information used in the analysis of the performance of the various sensors was gathered in two ways. Basic information on each sensor system was extracted from published documents. This information set was expanded by conducting in-depth discussions with the appropriate scientists and engineers who are involved in development of the instruments. These discussions and the document reviews were aimed at obtaining the latest, most complete data on the following aspects of each instrument,

- Operating principles
- Physical properties and power requirements
- Instrument characteristics
- Performance
- Data handling
- Limitations
- Spatial resolution

Formal discussions were held with the following personnel,

Instrument	Name	Organization
COPE/CIMATS	P. LeBel	NASA/LRC
" / "	M. Bortner	General Electric
DARS	R. K. Seals	NASA/LRC
"	F. Allario	NASA/LRC
MAPS	H. Reichle	NASA/LRC

TABLE 4-1
SUMMARY OF REMOTE SENSOR CHARACTERISTICS

(NUMBER IN PARENTHESES ARE FOOTNOTE INDICATORS)

INSTRUMENT	VOLUME (m^3) PRESENT	VOLUME (m^3) FUTURE	WEIGHT (Kg) PRESENT	WEIGHT (Kg) EXPECTED FUTURE	POWER (w)(3) PRESENT SURGE	POWER (w)(3) PRESENT AVERAGE	POWER (w)(3) FUTURE SURGE	POWER (w)(3) FUTURE AVERAGE	DATA OUTPUT ANALOG/ DIGITAL	DATA OUTPUT TIME PER REEL(1)	DATA OUTPUT BIT RATE (BAUD)	DATA PROCESSING PREPROCESSING	DATA PROCESSING BITS/BYTE	DATA PROCESSING CPU TIME/ POINT
COPE INSTRUMENT ELECTRONICS DATA RECORDER TOTAL	0.11 EST 0.03	0.11 EST 0.03	15.9 13.6 EST 22.7 52.2	15.9 13.6 EST 22.7 52.2	-- -- -- --	60 EST 80 140	-- -- -- --	60 EST 80 140	D	1 hr.	1024	R	NEG.	0.1s
CIMATS INSTRUMENT ELECTRONICS DATA RECORDER TOTAL	0.11 EST 0.03 0.14	0.11 EST 0.03 0.14	15.9 13.6 EST 22.7 52.2	15.9 13.6 EST 22.7 52.2	30 -- --	30 EST 80 110	40w -- --	30w EST 80 110	D	1 hr.	1024	R	NEG.	0.1s
DARS INSTRUMENT ELECTRONICS DATA RECORDER TOTAL	0.45 EST 0.03 0.48	0.45 EST 0.03 0.48	-- -- --	20-23 EST 22.7 4.27-45.7	-- -- --	-- -- --	-- -- --	5 EST 80 85	A	>3 hrs.	--	R	--	--
GFCI INSTRUMENT & COOLER ELECTRONICS DATA RECORDER TOTAL	0.34 0.01 EST 0.03 0.38	0.34 0.01 EST 0.03 0.38	124.7 EST 22.7 147.4	124.7 EST 22.7 147.4	-- -- --	EST 65 EST 80 EST 145	-- -- --	EST 65 EST 80 EST 145	A	2 hrs.	840	R	--	
MODIFIED GFCI INSTRUMENT & COOLER ELECTRONICS DATA RECORDER TOTAL	0.34 0.01 EST 0.03 0.38	0.34 0.01 EST 0.03 0.38	124.7 EST 22.7 147.4	124.7 EST 22.7 147.4	-- -- --	EST 65 EST 80 EST 145	-- -- --	EST 65 EST 80 EST 145	A	2 hrs.	840	R	--	EST 30s PLUS 70-500s FOR CALIBRATION CURVE
MAPS INSTRUMENT & COOLER ELECTRONICS DATA RECORDER TOTAL	0.34 0.01 EST 0.03 0.38	0.34 0.01 EST 0.03 0.38	136.0 EST 22.7 158.7	68.0 EST 22.7 90.7	-- -- --	65 EST 80 EST 145	-- -- --	65 EST 80 EST 145	D	2 hrs.	840	R	8	
HSI INSTRUMENT ELECTRONICS POWER SUPPLY DATA RECORDER TOTAL	0.23 EST 0.04 EST 0.02 EST 0.03 0.32	0.23 EST 0.04 EST 0.02 EST 0.03 0.32	1134.0 1134.0	78.6 167.8 104.3 22.7 541.2	4300 4300	2850 2850	-- --	1500 1500	D	20 min.	5000	NR	14	91s
LACATE INSTRUMENT RADIOMETER ELECTRONICS INTERFACE ELECTRONICS SOLID CRYOGEN COOLER DATA RECORDER TOTAL	0.06 0.01 0.14 EST 0.03 0.24	0.06 0.01 (4) EST 0.03 0.10	18.1 5.45 5.45 34.0 EST 22.7 85.7	18.1 5.45 5.45 11.3 EST 22.7 63.0	22 0 19 0 19 0 0 -- --	11.0 17.0 17.0 0 EST 80 125	22.0 19.0 19.0 0 -- --	11.0 17.0 17.0 0 EST 80 125	D	2 hrs.	1080	NR	12	0.05s
LIDAR INSTRUMENT ELECTRONICS DATA RECORDER TOTAL	0.17 EST 0.01 EST 0.03 0.21	0.17 EST 0.01 EST 0.03 0.21	317.5 22.7 440.2	272.1 22.7 294.8	-- -- --	1000 EST 80 1080	-- — --	600 EST 80 680	D	--	4000	NR	--	20s

INSTRUMENT	FIELD OF VIEW	CRYOGENICS	WARM-UP TIME	ORIENTATION	AVAILABILITY DATE	MATERIALS OBSERVED	WAVELENGTH μ	ACCURACY	MINIMUM DETECTABLE CONCENTRATION	RESPONSE TIME (μs)	DYNAMIC RANGE
COPE	7°(2)	DRY ICE/ GLYCOL 195°K	>2 hr.	ANY	EXISTS	CO CH_4	2.35 2.35	100 ppb 10 ppb	0.02 a-c 0.02 a-c	1 1	0.02-20 a-c 3 db
CIMATS	7°(2)	THERMO/ ELECTRIC 195°K	>2 hr.	ANY	1975	CO CH_4 CO_2 NH_3 NO NO_2 N_2O SO_2 C_2H_6 C_2H_4	2.35 2.35 2.0 2.2 5.3 6.1 2.9 7.3 3.35 3.35	EST 10% EST 10% EST 10% EST 10% EST 10% EST 10% EST 10% EST 30% EST 10% EST 10%	25 ppb 10 ppb 1200 ppb 10 ppb 0.1 ppb 0.03 ppb 10 ppb 0.03 ppb 2.5 ppb 0.1 ppb	1 1 1 1 1 1 1 1 1 1	40 db 3 db 25 db -- 300 db -- 25 db -- --
DARS	EST 10mr.	N_2 77°K AND He OR CLOSED CYCLE COOLER 4.2°K	EST.15 min.	ANY	1975	CO NO CH_4	-- -- --	EST 20% EST 20% EST 20%	32 ppb 5.3 ppb 56 ppb	10^6 10^6 10^6	EST 30 db EST 30 db EST 30 db
GFCI	7.5°	N_2 77°K	3-4 hrs.	ANY	EXISTS	CO	4.6	10%	--	10^6	0-3 ppm
MODIFIED GFCI	7.5°	N_2 77°K	3-4 hrs.	ANY	MID 1974	SO_2	4.0 OR 8.6	EST <10%	--	10^6	--
MAPS	7.5°	THERMO/ ELECTRIC 195°K	3-4 hrs.	ANY	OCT. 1974	CO CO_2 SO_2 NO_2 NH_3 CH_2O	4.6 2.1 4.0 OR 8.6 3.3 OR 7.6 3.0 OR 10.5 3.5	10% 1% EST <10% -- 5% ±2 ppb	-- -- -- -- -- --	10^6 -- 10^6 -- -- --	0-3 ppm -- -- -- -- --
HSI	>1.0°	N_2 77°K	<15 min.	ANY	EXISTS	CO CO_2 NO NO_2 N_2O SO_2 HNO_3 HCl CH_4 C_2H_2 C_2H_6 H_2CO O_3 H_2O NH_3 H_2O_2	4.67 4.26 5.33 6.18 4.5 7.34 7.56 3.47 3.31 3.04 3.35 3.59 4.74 6.27 2.99 2.92	-- -- -- -- -- -- -- -- -- -- -- -- -- -- -- --	1.0 ppb 0.2 ppb 4.0 ppb 0.4 ppb 0.4 ppb 3.0 ppb <5.0 ppb 1.0 ppb 2.0 ppb 3.0 ppb 2.0 ppb 1.0 ppb 50.0 ppb 1.0 ppb 1.0 ppb 10.0 ppb	10^6 10^6 10^6 10^6 10^6 10^6 10^6 10^6 10^6 10^6 10^6 10^6 10^6 10^6 10^6 10^6	-- -- -- -- -- -- -- -- -- -- -- -- -- -- -- --
LACATE	0.25-1mr.	N_2 77°K	<30 min.	NOT AT GROUND, NOT AT SUN	1975	CO_2 (BROAD) CO_2 (NARROW) O_3 HNO_3 N_2O H_2O CH_4 NO_2 AEROSOLS	15 15 9.6 11.3 17.1 6.3 7.78 6.2 >10.8<	-- -- ±10% ±15% ±10% ±10% ±13% 1-2 ppb —	EST 1 ppb EST 1 ppb EST 1 ppb EST 1 ppb EST 1 ppb EST 1 ppb EST 1 ppb EST 1 ppb EST 1 ppb	EST 1 EST 1 EST 1 EST 1 EST 1 EST 1 EST 1 EST 1 EST 1	0.0043-9.0W 0.0038-5.0W 0.0014-2.7W 0.0007-0.4W 0.0032-0.4W 0.0007-0.25W 0.0007-0.35W 0.00073-0.08W 0.0007-0.4W
LIDAR	20 mr.	NR	5 min.	ANY	6 MONTHS	AEROSOLS MIXING HEIGHT	0.59	100m	10^6 PARTS/m^3 --	10^{-3} 10^{-3}	80 db

INSTRUMENT	LIMITATIONS FLIGHT PLAN	VIBRATION	RFI	DAY/NIGHT OPERATION	CLOUDS	SMOKE	GROUND PATTERN	SAFETY	SPATIAL RESOLUTION OPERATING CONDITION	PLATFORM VELOCITY 15.4m/s ALTITUDE 200m	500m	1000m	PLATFORM VELOCITY 30.9m/s ALTITUDE 200m	500m	1000m	OPERATORS(5) PRESENT	OPERATORS(5) FUTURE
COPE	MI	NI	NI	DAY	I	MI	NI	NI	° FIELD OF VIEW ° FIELD OF VIEW 1 s scan	48m 38m	74m 44m	125m 55m	84m 75m	107m 81m	150m 90m	2	0
CIMATS	MI	NI	NI	DAY	I	MI	NI	NI	° FIELD OF VIEW ° FIELD OF VIEW 1 s scan	48m 38m	74m 44m	125m 55m	84m 75m	107m 81m	150m 90m	2	0
DARS	MI	NI	MI	ANY	I	I	I	NI		36m	37m	40m	72m	74m	77m	1	1/2
GFCI	MI	I	I	ANY	I	MI	I	NI	.5s TIME CONST. .0s TIME CONST. .0s TIME CONST.	34m 49m 186m	67m 78m 208m	131m 133m 247m	51m 85m 370m	79m 110m 391m	134m 157m 427m	1/2	0
MODIFIED GFCI	MI	I	I	ANY	I	MI	I	NI	.5s TIME CONST. .0s TIME CONST. .0s TIME CONST.	34m 49m 186m	67m 78m 208m	131m 133m 247m	51m 85m 370m	79m 110m 391m	134m 157m 427m	1/2	0
MAPS	MI	I	I	ANY	I	MI	I	NI	.5s TIME CONST. .0s TIME CONST. .0s TIME CONST.	34m 49m 186m	67m 78m 208m	131m 133m 247m	51m 85m 370m	79m 110m 391m	134m 157m 427m	1/2	0
HSI	MI	NI	NI	ANY	I	MI	NI	NI	--	2700m	2700m	2700m	5400m	5400m	5400m	2	0
LACATE	MI	I	MI	ANY	I	I	NI	NI	VERTICAL RESOLUTION AT 10Km ALTITUDE	O_3-0.4Km HNO_3-0.4Km N_2O-0.8Km H_2O-0.8Km CH_4-0.8Km NO_2-0.8Km						0	0
LIDAR	MI	NI	I	ANY	I	I	NI	I		4	10	20	4	10	20	1/2	1/2

ABBREVIATIONS AND SYMBOLS

A	Analog
ANY	No Restriction
a-c	Atmosphere-centimeters
D	Digital
db	Decibel
EST	Estimate
hr(s)	Hour(s)
I	Important factor
°K	Degrees Absolute
Kg	Kilograms
m	Meters
MI	Moderately Important Factor
min.	Minutes
mr.	Milliradians
m/s	Meters Per Second
NEG.	Data not Important for Present Application
NI	Not an Important Factor or no Effect
NR	Not Required
ns	Nanosecond
R	Required
s	Second
W	Watts/Square Meter-Steradian
w	Watts
μ	Microns
μs	Microsecond
--	Information not Available or Unknown

(1) Time per reel is based on one standard 35 cm (14 inch) diameter reel of magnetic tape.
(2) With foreoptics may be reduced to 2°.
(3) All instruments except HSI operate on 28V/DC. HSI operates on 120V/60 cycle.
(4) Cooler volume included with instrument.
(5) Zero indicates automatic or near automatic operation with operator only doing a few simple tasks such as turning switches on and off periodically. One half indicates any part time operator.

FOLDOUT FRAME 1

FOLDOUT FRAME 2

FOLDOUT FRAME 3

Instrument	Name	Organization (Cont)
MAPS	H. Orr	NASA/LRC
"	S. Beck	NASA/LRC
HSI	C. B. Farmer	Jet Propulsion Lab
"	R. Toth	Jet Propulsion Lab
LACATE	J. Russell	NASA/LRC
LIDAR	B. Northam	NASA/LRC
In-Situ Sampling	H. Reichle	NASA/LRC
"	D. Wornom	NASA/LRC
"	R. Evans	NERC/Las Vegas

All information gathered in the initial formal discussions was analyzed and a draft document covering the topics listed above was prepared for each instrument except the in-situ samplers. These documents were submitted to at least one of the persons listed above for each instrument for technical review and changes were made as deemed necessary by the reviewer. The information presented in the remainder of Section 4 of this report is essentially similar to that previously prepared for these documents.

4.2 Analysis of Sensor Performance

In this section the terms listed below have the definitions indicated:

- Resolution - for a stationary non-scanning sensor the geographical area on the ground or at some point in space observed by the instrument; for a scanning sensor or a sensor on a moving platform,

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the area defined above plus the area traversed by the stationary resolution during the time required to adequately respond to a step forcing function. Adequate response is defined to be 90% of the step function.

- Lagtime - the time from exposure of an instrument to a step forcing function until the first response is noted in the output signal. In general, this refers to instruments which made contact measurements through plumbing.
- Collection time - the time required to accumulate data for one output value. In general, this refers to interferometric devices.
- Response time - the time required to reach 67% of the amplitude of a step forcing function.

4.2.1 COPE/CIMATS

4.2.1.1 Carbon Monoxide Pollution Experiment (COPE)[1]

- Operating Principles

A correlation interferometer (COPE) has been developed for the measurement of carbon monoxide and methane at 2.35 microns in both the troposphere and the stratosphere using reflected sunlight. A Michaelson interferometer principal is used but the delay is not achieved by moving one of the mirrors. Instead the delay is achieved by use of a moving compensator plate which varies the path difference over a distance of a few millimeters (viz. 2.7 to 3.95 mm according to Bortner). (This is in contrast with the High Speed Interferometer which has a much larger variation in path difference, on the order of 1 cm). The

[1] References used in the COPE analysis are listed at the end of this Section 4.2.1.

interferogram produced represents many gases and is analyzed on the computer by correlation with known interference patterns. The actual printout from the computer consists of the amount of the pollutant (atm-cm), which is a measure of the column density, and the time of the measurement which can be correlated with the spatial location of the instrument. The data processing is much simpler than that for the high speed interferometer (HSI) for two reasons. The first is that a smaller number of interference steps are used in COPE and the second is that the interferogram is not inverted into the absorption spectrum for final analysis. Both of these facts greatly reduce the processing required.

As stated above the operating wavelength used for detecting carbon monoxide and methane is 2.35 microns. The band width is from 10 to 25 wave numbers. The COPE instrument is reported to have tropospheric sensitivities of 100 ppb for methane and 10 ppb for carbon monoxide.

A particular advantage of this instrument is its ability to operate at wavelengths below 3.5 microns thus observing reflected sunlight. This eliminates the problem which infrared instruments encounter which prevents observation of emissions from the lower atmosphere where the temperature contrast between the earth and the atmosphere is small. Principal disadvantages of the instrument are the need for a cloudless line of sight and the probability that the instrument will not operate at night.

An engineering model of the instrument has been flight tested on a small jet aircraft and it has operated as designed. Therefore, the instrument is considered to be close to available for operational use.

- Physical Properties & Power Requirements

Weight - Instrument, 15.9 kg; Electronics, 13.6 kg.

Volume - Instrument, 0.30 meters by 0.35 meters by 0.50 meters; Electronics, 2 standard 0.48 meter panel racks. Total volume is approximately 0.1 cubic meters.

Power - 60 watts for the present engineering model. Instrument can tolerate a 10% power variation without appreciable effect. Power surge information is lacking at the present time.

Volts - 28 volt DC.

- Instrument Characteristics

Calibration - The instrument has a built in black body radiator and a sample gas cell for calibration. Calibration is normally checked every 15 minutes or less. The instrument also has automatic gain control and a CO_2 detector built in.

Drift - The principal investigator reports that no instrument drift problems have been encountered to date. However, it is admitted that this subject has not been thoroughly investigated.

Cryogenics - The engineering model operates in the 195° to 200°K range using a dry ice-glycol cooler. Cool down time is approximately 15 minutes with 30 minutes stated as the probable maximum.

Personnel Required - The engineering model is ideally operated by two men but can be handled by one. There is no theoretical or practical reason why the instrument could not be fully automated.

Field of View - The normal instrument has a 7° field of view. With telescopic fore optics the field of view can be reduced to 2°.

Scanning - The instrument is not designed for scanning at present but there is no reason why it could not be modified to scan.

Operating Conditions - It is desired to maintain the instrument within a range of $10^{o}K$. Water vapor or relative humidity presents no problem.

Auxiliary Measurements - A measurement of the CO_2 column density is required. This is measured with the built in CO_2 detector.

Orientation - The instrument may be oriented in any direction.

Warm-up Time - The instrument requires several hours for warm up of the optical system.

- Performance

Materials - CO, CH_4

Accuracy - Laboratory tests indicate an accuracy of 10% or better in measuring the column density of carbon monoxide.

Resolution - The spatial resolution of the instrument is a function of the field of view, which is fixed, and the angle of elevation of the sun above the horizon which is a variable. This is due to the fact that the detected solar radiation has passed through the polluted atmosphere at an angle and is reflected upward from the earth through the polluted atmosphere to the detector. Absorption occurs during both passages. The cognizant engineer states that the developers of the instrument are aware of this problem but have not made a determination of its effect on resolution. Studies of vertical profiles of pollutants are underway with the objective of resolving this problem. Ideal operating conditions for the instrument would be with the sun directly overhead. This would yield a ground resolution of approximately 130 meters from a stationary platform at an altitude of 1000 meters for the 7° field of view instrument.

Minimum Detectable Concentration - 0.02 atm-cm for carbon monoxide and methane.

Lagtime - The lagtime is zero.

Collection Time - The collection time for one scan is one second.

Response Time - The instrument response time is in the microsecond range.

Dynamic Range - The dynamic range for carbon monoxide is from 0.02 atm-cm to 20 atm-cm.

Altitude - There is no reason for preferring any particular altitude.

- Data Handling

Analog or Digital - The output of the instrument is recorded digitally on magnetic tape in computer compatible format. A fourteen track tape recorder was used in recent flight tests.

Time per reel - The data from one hour of continuous instrument operation can be stored on one 35 cm. diameter reel of tape.

Preprocessing - At present, the cognizant engineer feels that the preprocessing involves at least the demodulation of an FM signal and subsequent formatting. It takes about 1 hour of preprocessing per hour of data to produce a computer compatible tape (CCT).

CPU Time per Point - The processing of each data point requires approximately 0.1 sec. of CPU time.

Bit rate - Data rates are very low for the COPE instrument. In the engineering model a scan of 32 sample points would require no more than 1024 bps.

The results of the processing are presented in the form of the magnitude of the pollutant in the column (includes the vertical column below the sensor and the slant column to the sun) and the time of the reading. Geographical location is determined from platform navigation data.

- Limitations

Atmospheric - The COPE instrument will not detect through clouds. Therefore operation must be on a cloudless day or limited to line of sight. The principal investigator suggests that flights be limited to days with 10% clouds or less. The major consideration is a clear sunlight path.

Flight Plan - There are no restrictions on any flight plan. However it is recommended that the sun angle be more than 30° from horizontal.

Day/Night Operation - The instrument probably will not operate at night. Dr. Bortner* states that theoretically this instrument could operate with any source in this wavelength; therefore, moonshine cannot be eliminated at this juncture.

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*Bortner, M., private communication, General Electric Co., November 1973.

Vibration - The instrument has flown on both conventional and helicopter aircraft with no problem without special shock mounting.

Radio Frequency Interference - RFI was not a problem on any of the flights.

Smoke - The principal investigator feels that the presence of smoke in the atmosphere probably interferes with the instrument reading. However, it is not judged to be serious.

Ground Pattern - No problems have been encountered which could be attributed to the background pattern on the ground.

Safety - There are no safety problems.

- Spatial Resolution

For the purposes of this work, a most important figure of merit of various remote sensors is the spatial resolution. This determines the ability of the device to resolve variations in pollution concentration and to identify the area of the ground which the device is monitoring at a given time.

Consider a sensor which "sees" to the ground* and has a square footprint of side D. Several factors influence how quickly (or over what distance of travel of the platform) the sensor detects the changes in pollution concentration. The factors are:

*Clearly this only occurs under special conditions for the COPE/CIMATS instruments. Here we assume that the ground level concentration is so much higher than that of the rest of the air column so that only the ground level is measured.

Aircraft velocity	V
Time constant of instrument	Υ
Lag time of instrument	T
Field of view	Ω
Altitude	R
Footprint dimension	$\Omega R=D$

For this instrument, two regimes of resolution will exist. First, if the volocity of the aircraft is low such that the footprint, D, exceeds the product of the velocity and the collection time, then the limit is D.

If, however, V times the collection time exceeds D, then that product is the resolution limit.

The resolution of the instrument appears to be less than 100 meters for a wide range of operating conditions. This would appear to give adequate resolution when compared with spatial variation predicted by models of SO_2 and CO distributions in the Washington, D.C. area. However, the resolution of the model is also on the order of 100 meters which prevents it from constructing variations in pollution concentration which occur over ranges smaller than that distance. Figure 4-1 illustrates the resolution of the COPE instrument under a variety of conditions. These conditions include aircraft velocity, aircraft altitude and instrument field-of-view.

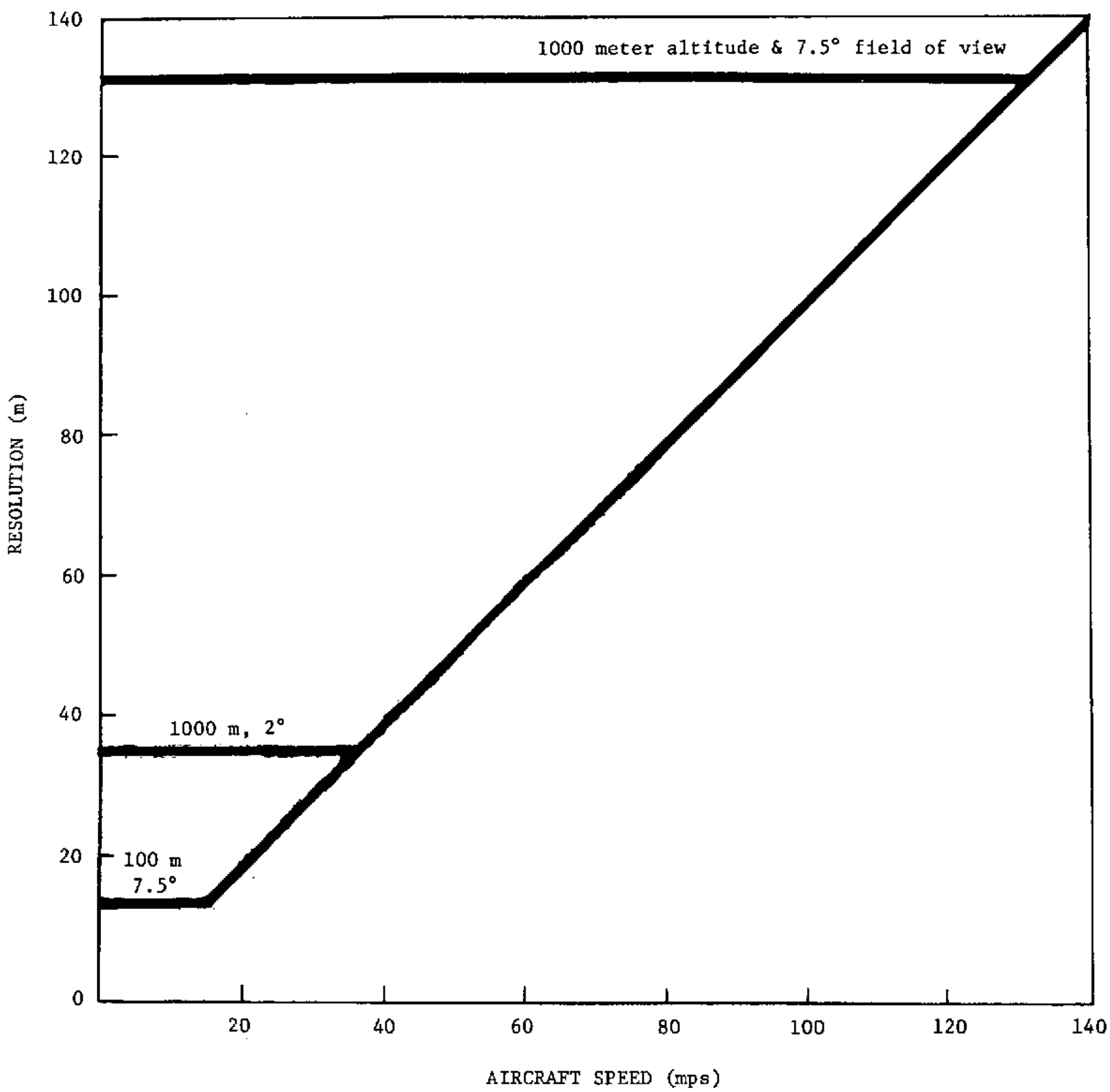

FIGURE 4-1
COPE RESOLUTION

4.2.1.2 Correlation Interferometric Measurement of Atmospheric Trace Species (CIMATS)[1]

- **Operating Principles**

A correlation interferometer similar to the COPE instrument is being developed for multi-pollutant measurement. The instrument is called the correlation interferometer for measurement of atmospheric trace species (CIMATS). Basically the instrument is the same as COPE with additional spectral filters used for the various gases of interest. The exact manner in which these filters will be shifted during operation has not been determined yet. All other characteristics of the instrument will be similar to the COPE instrument except as noted below.

The pollutants currently under consideration for inclusion in the CIMATS instrument are listed below:

Pollutant	Wavelength of interest (μ)	Estimated Sensitivity (ppb)
Methane, CH_4	2.35	25
Carbon monoxide, CO	2.35	10
Carbon dioxide, CO_2	2.0	1200
Ammonia, HN_3	2.2	10
Nitric oxide, NO	5.3	0.1
Nitrogen dioxide, NO_2	6.1	0.03
Nitrous oxide, N_2O	2.9	10
Sulfur dioxide, SO_2	7.3	0.03
Ethane, C_2H_6	3.35	2.5
Ethylene, C_2H_4	3.35	0.1

[1] References used in the CIMATS analysis are listed at the end of this Section 4.2.1.

In the final configuration this list will probably be reduced to 5 or 6 gases. It is expected that all of the above gases, except SO_2, will be measured with accuracies on the order of 10%. For SO_2 the most likely accuracy is 30%.

The inclusion of SO_2 will necessitate a fundamental change in the COPE version of the instrument. In order to construct the interferogram for the 7.3μ wavelength the moving compensator plate must be shifted so that the 1.5mm scan is centered at 7.3μ. It may be that this selected delay range is suitable for several gases. However since 7μ is well into the thermal IR region the instrument is no longer observing reflected sunlight but thermal emission from the earth and the atmosphere. This will prevent the instrument from observing emissions from the lower atmosphere where the temperature contrast between the earth and the atmosphere is small. The principal investigator estimates that a difference of a few degrees K is required. This ΔT agrees with what other investigators have reported and will limit measurement to above 500 meters altitude for a standard atmosphere. The best readings can be expected in the middle of a clear day when cold air is flowing over warm ground or water.

- Instrument Characteristics

The CIMATS instrument is expected to have a total weight of 22.7 kg. including electronics. Its dimensions will be approximately the same as COPE. The required power is expected to average 30 to 40 watts. Detector cooling will be thermo-electric.

Data handling and processing will be similar to the COPE instrument. Total data rates and volume will not increase since the instrument will operate sequentially for each gas rather than in parallel.

The time required to make one complete set of measurements will be 5 or 6 seconds plus the time required to mechanically change the filters in the fore optics. This later time cannot be determined until the method of filter changing is selected.

COPE References

1. NASA/LRC Staff. "Environmental Quality Enhancement Study." December 1972.

2. NASA/LRC Staff. "Nimbus G Atmospheric Quality Experiments", August 1972.

3. NASA/LRC Staff. "Presentation of LRC Air Pollution Research Programs to Office of Applications", February 1972.

4. Lawrence, J. and L. Keafer, Jr. "Remote Sensing of the Environment", Presented to Interagency Conference on the Environment, Lawrence Livermore Laboratory, October 1972.

5. Bortner, M. H. et al. "Carbon Monoxide Pollution Experiment III. Instruments and Measurements", APCA-72-18, Presented at the 65th Annual Meeting of the Air Pollution Control Association, June 1972.

6. University of Michigan, Aerospace Engineering Staff. "SCOPE, a Satellite for Carbon Monoxide Pollution Evaluation", April 1972.

7. Bortner, M. H. et al. "Development of a Breadboard Model Correlation Interferometer for the Carbon Monoxide Pollution Experiment", NASA CR-112212, General Electric Co., Philadelphia, March 1973.

8. Goldstein, H. W. et al. "The Remote Measurement of Trace Atmospheric Species by Correlation Interferometry. I. Carbon Monoxide and Methane", Presented at the Second Joint Conference on the Sensing of Environmental Pollutants, December 1973.

COPE References (Continued)

9. Goldstein, H. W. et al. "Correlation Interferometric Measurement of Trace Species in the Atmosphere", Presented at AIAA/AMS International Conference on the Environmental Impact of Aerospace Operations in the High Atmosphere, June 1973.

10. Grenda, R. N. et al. "Carbon Monoxide Pollution Experiment - (I). A Solution to the Carbon Monoxide Sink Anomaly", Presented at the First Joint Conference on the Sensing of Environmental Pollutants, November 1971.

11. Bortner, M. H. et al. "Analysis of the Feasibility of an Experiment to Measure Carbon Monoxide in the Atmosphere", General Electric Co. Philadelphia, Undated but estimated Summer 1973.

12. LeBel, P. J. and M. H. Bortner: Private communication, November 1973.

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1. NASA/LRC Staff. "Environmental Quality Enhancement Study." NASA Langley Research Center, December 1972.

2. Lawrence, J. and L. Keafer, Jr. "Remote Sensing of the Environment." Presented to Interagency Conference on the Environment, Lawrence Livermore Laboratory, October 1972.

3. Keafer, L. Jr. "Development of Flight Experiments for Remote Measurement of Pollution." Presented at the Second Annual Remote Sensing of Earth Resources Conference, March 1973.

4. LeBel, P. J. and M. H. Bortner, Private communication, November 1973.

5. Goldstein, H. W. et al. "The Remote Measurement of Trace Atmosperic Species by Correlation Interferometry. I. Carbon Monoxide and Methane." Presented at the Second Joint Conference on the Sensing of Environmental Pollutants, December 1973.

6. Goldstein, H. W. et al. "Correlation Interferometric Measurement of Trace Species in the Atmospheric." Presented at AIAA/AMS International Conference on the Environmental Impact of Aerospace Operations in the High Atmosphere, June 1973.

7. Bortner, M. H. et al. "Analysis of the Feasibility of an Experiment to Measure Carbon Monoxide in the Atmosphere." General Electric Co., Philadelphia, Undated but estimated Summer 1973.

4.2.2 Differential Absorption Remote Sensing (DARS)

- Operating Principles

DARS utilizes a tuneable solid-state infrared laser operating at 4.2^{o} Kelvin. Radiation from this laser is transmitted through the atmosphere at a wavelength which is selectively absorbed by a pollutant of interest. The partially absorbed radiation reaches the ground and is reflected upwards toward the receiver. The total radiation detected is then a function of the total burden of pollution, the reflectivity of the earth and the laser power. The changes in surface reflection can be ignored by operating the laser in a mode which alternates the operating wavelength between the absorption wavelength and another wavelength outside of the absorption band but which has the same reflectivity coefficient. The use of 2 laser lines is adequate to provide the total burden in an atmosphere uniformly mixed with the gas of interest. In a more stratified atmosphere more lines must be used. One of these lines still gives the reflectivity of the earth. The others are positioned in wavelength so that they interact with the gas in different degrees. In this way, very little of the radiation directly centered on the absorption line of the gas will return if regions of the atmosphere have high densities of the gas. However, a laser emission positioned on the skirt of the absorption propagates with more efficiency. Use of the detected signals and knowledge of the pressure broadening characteristics of the gas allows complete analysis of the problem. Use of n + 1 laser lines will provide the total burden in an atmosphere strategied in n layers.

Because of the relatively low power output (≈50mw), sophisticated receiver techniques must be used. In this case, heterodyne detection is used. In such a system, the atmosphere can be stratified into 3 layers if 50mw of power are available. The laser can be operated either as a pulsed or continuous source. In either case it is used as the local oscillator in the heterodyne system. In the continuous mode, electromechanical chopping and phaselock detection is used.

- Physical Properties and Power Requirements

Weight - 20-23 kg.

Dimensions and Volume - The instrument occupies a region 0.6 by 0.6 by 1.3 meters plus the volume of the receiver and the data handling electronics.

Power - The laser transmitter consumes only 5 watts. The data handling system can be expected to consume significantly more than that. Power can be provided from the aircraft's 28 volt DC system or a portable battery pack.

- Instrument Characteristics

Calibration - Measurements must be made of the operating wavelength of the laser and the power emitted (average for the CW case and peak of the pulsed case). Wavelength stability is monitored with a sample gas cell utilizing a correlation technique discussed under Warm-up considerations.

Draft - The major drift is in the wavelength of operation of the laser due to temperature changes at the location of the laser in the helium cryostat. A feed-back system is used for temperature stabilization.

Cryogenics - Liquid helium is used to cool the laser diode and liquid nitrogen is used to cool the detector. Closed cycle cooling can also be used.

Operator - One technician is required to operate the instrument and he will be fully devoted to this task. Full automation is foreseeable in the future.

Field of view - 10 milliradians.

Scanning - This feature could be provided if required.

Operating Conditions - As in any other optical instrument condensation must be avoided to guarantee peak performance and avoid degradation of optical coatings. Appropriate protection is required.

Auxiliary Measurements - None are required although a vertical temperature profile can be used to remove second order effects.

Orientation - Any orientation can be used. Some consideration is being given to mounting the transmitter on the tail of a large aircraft and, using a retro-reflector on a wing tip, measuring the pollution along that path, but the results may be influenced by local pollution effects.

Warm-Up Time - Only the electronics need be warmed-up so this can be expected to be on the order of minutes. The major limitation appears at this time to be the ability to stabilize the temperature of the laser diode within 10 millidegrees for periods of weeks so that a complete calibration procedure and flight pattern can be performed with the diode under the same conditions. Although this is a solvable problem, it will add complications to what is basically a simple experiment. The wavelength stabilization gas cell and current feedback control technique is expected to be the solution for this problem. The reliability of the instrument is expected to be good since one laser diode has already exceeded 600 hours of operation with no failure.

Availability Data - This instrument will not be available for at least 2 years. A version utilizing a tuneable CO_2 gas laser for detection of SO_2 and NH_3 will be available in about 1 year.

- Performance

Materials - This device is sensitive to those atmospheric constituents which have absorption bands and lines in the range 3 - 30 microns.

Accuracy - Generally the accuracy can be expected to be $\pm$ 20% or better although this is a function of the gas in question and other factors. This 20% accuracy figure refers to a DARS instrument at an altitude of 5 km.

Resolution - From an altitude of 5 km, the vertical resolution is expected to be 1 km. This figure is based on at least some atmospheric modeling.

Using the analysis technique reviewed in the discussion of the MAPS unit (4.2.3) and the instrument parameters previously discussed, the horizontal resolution of the DARS instrument is, for specific examples:

Velocity, (mps)	15	15	15	31	31	31
Altitude, (m)	200	500	1000	200	500	1000
Resolution, (m)	36	37	40	72	74	77

Minimum Detectable Concentration - From an altitude of 5 km.

CO	32 ppb
NO	5.3 ppb
CH_4	56 ppb

Lag Time - Not applicable

Collection Time - Not applicable

Response Time - The one over e-time is expected to be around 1 second for powers in the milliwatt range.

Dynamic Range - This is a function of the gas being detected but averages about 30 db (30 to 1). Instrument modifications should improve this figure.

Altitude - The optimum altitude is not well defined since higher altitudes increase the total burden but produce smaller signals. In all likelihood, the altitude and wavelength of operation will have to be adjusted at the same time to guarantee the best results.

- Data Handling

Analog or Digital - This instrument produces analog voltages which are recorded on magnetic tape. Digital output could also be provided with an appropriate converter.

Time per reel - The data rate is such that a standard reel of analog magnetic tape is adequate to record an entire flight of several hours duration. The actual tape consumption rate is not known.

Preprocessing - This is required for analog to digital conversion and coding in computer compatible language.

- Limitations

Atmospheric/Meteorologic - Turbulence, scattering, rain and fog limit the performance as expected.

Flight Plan - This is not an influential factor in system performance.

Day/Night - This device can be operated at any time.

Vibration - Vibration is expected to be only a minor problem.

RFI - The instrument is expected to be only mildly influenced by RFI and produce very little interference of it's own. Major problems could arise due to the high sensitivity of the instrument.

Smoke - The influence of smoke is not known. A general problem with scattering due to particulates is anticipated.

Ground Pattern - For best results, consistent reflectivity is required. An AGC system could help relax this constraint.

Safety - The only safety problem concerns the handling of liquid nitrogen and helium. Both cryogenics dewars have eight hour capacity so that no addition of cryogen need take place during a normal flight.

DARS References

1. Allario, F. and R. K. Seals. Private communication at NASA, Langley Research Center, October 1973.

2. Seals, R. K. and C. Bair. "Analysis of Laser Differential Absorption Remote Sensing using Diffuse Reflection from Earth", Presented to the Second Joint Conference on Sensing of Environmental Pollutants, December 10-12, 1973, Washington, D.C.

4.2.3 Measuring Air Pollution From a Satellite (MAPS) Family of Instruments

4.2.3.1 Gas Filter Correlation Instrument (GFCI) For CO Detection

- Operating Principles

The GFCI device operates as a gas correlation filter analyzer. Thermal radiation from the ground (85%) and air (15%) is alternately passed through a sample of the gas of interest contained in an optical chamber and through an identical chamber which has been evacuated.

The relative transmission through the two cells is used to determine the total burden of pollutants within the field of view of the instrument and below the aircraft by use of a radiative transfer model. Use of vertical temperature and water vapor profiles is required for point by point determination of the total burden of pollutant.

Theoretically, this instrument will detect any gaseous pollutants which have absorption bands or lines within the wavelength limits of the device (2-20μ), assuming that strongly absorptive bands from water, etc. are not influential. The instrument under discussion here detects only CO at 4.6μ with 10% accuracy from 0 to 3 ppm.

- Physical Properties & Power Requirements

Weight - 123 kg.

Volume - 0.34 m^3, (1 x 0.6 x 0.6 meters)

Power - not known by NASA at this time.

Volts - 28 volts, DC from the aircraft electrical system will power the instrument.

The solid state detector will require cooling to liquid nitrogen temperatures either by liquid cryogen or thermoelectric cooling. Using the latter technique the weight and power consumed will rise by 25 pounds and 60 watts respectively.

- Instrument Characteristics

Calibration - An on-board calibration black-body exists as part of the instrument. Recalibration procedure must be performed on the present instrument every ten minutes or so.

Drift - This represents the major limit of the performance of the instrument. The main source is temperature drift in the entire instrument.

Cryogenics - Liquid nitrogen is required to cool the detector, if the thermoelectric cooler is not used.

Personnel Required - One operator is required for periodic inspection and calibration of the unit.

Field of View - 7.5^{o} (nominal) and could be reduced with external optics.

Scanning - This could be provided with installation of external electro-mechanical devices.

Operating Conditions - For optimum operation the unit should remain at a single temperature in the range 15-40^{o}C and humidity should be minimized. Moisture degrades the optical coatings. The temperature requirement has forced utilization of a heater system for high altitude flights.

Auxiliary Measurements - Temperature and humidity vertical profiles are required for complete data analysis.

Orientation - The unit will be used in a down-looking mode.

Warm-up time - The unit is ready for use after three or four hours of warm-up.

Availability - presently in use.

- Performance

Materials - CO

Accuracy, Minimum Detectable Concentration - The accuracy for CO measurements is expected to be $\pm$ 10%. The minimum detectable concentration is undetermined at this time.

Lagtime - The lagtime is zero.

Collection time - The data collection time is zero.

Response time - One second.

Dynamic Range - The instrument detects up to 3 ppm.

Altitude - Since the instrument was designed for satellite applications, it can see through the entire atmosphere. The low altitude restriction is discussed in the "Limitations" section.

- Data Handling

Analog or Digital - The instrument produces analog voltage output. On the present instrument this voltage drives analog magnetic tape and strip chart recordings. In the digital version, 8 bit words will be used.

Time per reel - A standard analog tape reel will be sufficient to store data taken during two hours of flight.

Preprocessing - Analog to digital and computer compatible tape conversion is necessary.

CPU time per point - A calibrated total burden of pollutant can be provided in 30 seconds if vertical profiles of temperature are measured or modeled. 70 - 500 seconds are required to generate the instrument calibration curves. These times refer to use of a CDC 6600 computer.

Bit rate - The information flow rate is 840 bits per second.

Data analysis and interpretation remains a concern with this instrument if only because of the large computer time required. Interpretation of the data is also time consuming and the anticipation is that a fully automated quasi-real-time system is far off. The data analysis is used to calibrate the column burden although relative concentrations may be obtained with less computation. Provision of calibrated ground-truth data would reduce the computation work by a large factor. In any case, vertical profiles of temperature and humidity are required for data analysis.

Use of a small on-board computer and data handling system is possible to provide quasi-real-time calibrated output.

In addition, vertical profiles may be derivable by flying at different altitudes. Vertical profiles of temperature and humidity must be provided either by support instrumentation aboard the aircraft or by coordinated RAOB data.

- Limitations

Atmospheric - As with any infrared device, water vapor clouds or precipitation severely limit the transmission of radiation and inhibit the performance of the system.

Flight Plan - The aircraft must not fly in its own wake since the aircraft's exhaust would significantly influence the instrument's output.

Day/Night - Since the unit detects thermal radiation from the earth and atmosphere, night as well as daytime operation is possible.

Vibration - This is a fairly severe limitation on the unit while in operation. Therefore future units will be shock mounted.

Radio Frequency Interference - The instrument is somewhat affected by interference generated in communication systems in the airplane.

Ground Pattern - Geometrically regular ground pattern (such as found in farming areas) causes some difficulty when the aircraft passes from a region of one ground emissivity to another.

Safety - There are no safety problems.

The most serious problem with the instrument itself appears to be a drift produced by a lack of temperature stability in the instrument and it's black-body reference. This defect requires re-calibration every 10 minutes. Further, since it is basically a differential temperature measuring device, it will not sense trace gases which are at the same temperature as the ground, which can prevent detection of gases at low altitudes. This is somewhat restrictive in light of the proposed goal of the project which is oriented toward correlation of remotely sensed data with actual ground measurements.

It has been estimated that a temperature differential of 3 degrees centigrade is adequate to differentiate between the atmosphere and water. Since land is a less effective black-body radiator than water, its effective radiative temperature is lower than that of water at the same real temperature, thus allowing discrimination between air and land under conditions which would be prohibitive when working over water. In general, this will mean adequate system performance for temperature differentials nearer 1 degree centigrade.

- Spatial Resolution

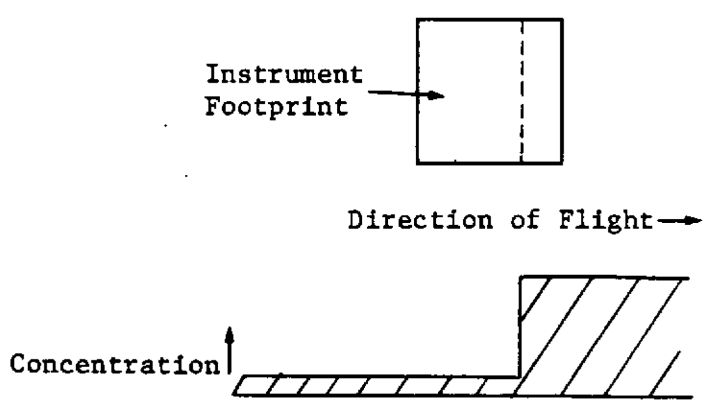
For the purposes of this work, a most important figure a merit of various remote sensors is the spatial resolution. This determines the ability of the device to resolve variations in pollution concentration and the identify the area of the ground which the device is monitoring at a given time.

Modeled distributions of carbon monoxide and sodium dioxide have been chosen from typical dates studied in Section 3. The influence of limitations of the models on the adequacy of the evaluation is discussed in Section 8.2.

Consider a sensor which "sees" to the ground* and has a footprint of side D. Several factors influence how quickly (or over what distance of travel of the platform) the sensor detects the changes in pollution concentration. The factors are:

aircraft velocity	V
time constant of instrument	τ
lag time of instrument	T
field of view	Ω
altitude	R
footprint dimension	$\Omega R = D$

Consider the following figure.



*Here it is assumed that either the weather conditions are such that the instrument sees close to the ground or that the vertical circulation of pollutants is such as to reflect to some degree the ground level distribution. The complete details of the following analysis are presented in Section 8.2.

As the footprint progresses across the discontinuity, each successive small area interacts with the changed concentration and adds its influence to the output of the device.

The problem can be divided into two time periods:

(1) $t < \frac{D}{V}$ (footprint only partially past step, as shown)

(2) $t > \frac{D}{V}$ (entire footprint past step)

1) $t<\frac{D}{V}$

$$\text{Response} = \frac{1}{D}\int_0^{Vt} [1-\exp(\frac{t-x/V}{\tau})]dx$$

Where it is assumed that the instrument electronics respond according to

$$1-e^{-t/\tau}$$

$$\text{Response} = \frac{Vt}{D} - \frac{V\tau}{D}(1-e^{-t/\tau})$$

If $\frac{V\tau}{D}$ is small (≈ 0.1)

$$\text{Response} \cong \frac{Vt}{D}$$

which is just the geometric increase in the viewed area.

2) $t>\frac{D}{V}$

$$\text{Response} = \frac{1}{D}\int_0^{D} [1-\exp(\frac{t-x/V}{\tau})]dx$$

$$=1-e^{-t/\tau}\ \frac{V\tau}{D}(e^{D/V\tau}-1)$$

If $D\approx 0$

$$\text{Response} \approx 1-e^{-t/\tau} \text{ as expected}$$

If $\frac{V\tau}{D} \approx 0$

Response $=1$ as expected

If we define the resolution as the distance the aircraft travels before the response reaches 90% of its final value, two cases emerge. If the time response is very quick, the resolution will only be limited by the field of view and 90% response will be achieved when 90% of the field of view has passed a particular point. Thus the resolution will be 0.9D (referred to as D for convenience) and t will be $<D/V$. In the second case, if the 90% point is reached for $t > D/V$ the instrument is limited by its time constant and field of view and the resolution is $Vt_{0.9}$ where $t_{0.9}$ is the time required for the instrument to reach 90%. The value $t_{0.9}$ is found by solving:

$$1-e^{-t_{0.9}/\tau} \ \frac{V\tau}{D} \ (e^{D/V\tau}-1) = 0.9$$

For this particular instrument, the limiting factor can be determined by evaluating $D/V\tau$. If $D/V\tau \lesssim 10$, 90% will be reached for $t>D/V$ and the device is limited by a combination of time constant and field of view. If $D/V\tau \gtrsim 10$, 90% is reached for $t<D/V$ and the field of view limit dominates.

Using this technique, the resolution of the GFCI was evaluated and the results are shown in Figure 4-2. The values of resolution indicated for the velocity and the fields of view of the instrument at the two altitudes, 100 and 1000 meters. In each case, as the velocity increases, the resolution progressively becomes linear, with the slope of the curve being determined by the time constant.

In order to establish how these values of resolution influence the performance of the instrument, a calculation was made, based on typical modeled CO data. A trajectory was drawn through the largest rate of change of CO concentration predicted for 7 A.M. July 18, 1972.

To allow for changes in concentration on a scale smaller than the model can compute, the peak of the concentration was multiplied by 10 while keeping the lower values constant. The resulting predicted pollution distribution is shown as the heavy line in Figure 4-3. The instrument response was then predicted in the following way: At each point on the pollution curve (shown by dots on the line) a summation was made of the contributions from each of the previous points. The contributions were evaluated by using

$$1-e^{-x/R}$$

where R is the calculated resolution and x is the distance between the point of interest and the contributing location. Thus, the equation for the response at point x is

$$\text{Response } (x) = \sum_i A_i \left[1-e^{-(x-x_i)/R} \right]$$

where the sum ranges over all values where $x-x_i$ are positive and where A_i is the amplitude at each point in the pollution distribution predicted by the model.

The spatial resolution of the CO dispersion model is of the order of 100 meters and the temporal resolution is of the order of one hour. The GFCI spatial resolution is of the order of several hundreds of meters and the temporal resolution is of the order of seconds. Therefore, actual measurements of the GFCI in the vicinity of CO source are likely to show more structure and concentration variation in the emission plume than is indicated by the model. However, for a variety of operating conditions (flight speed, altitude, time constant), the spatial resolution

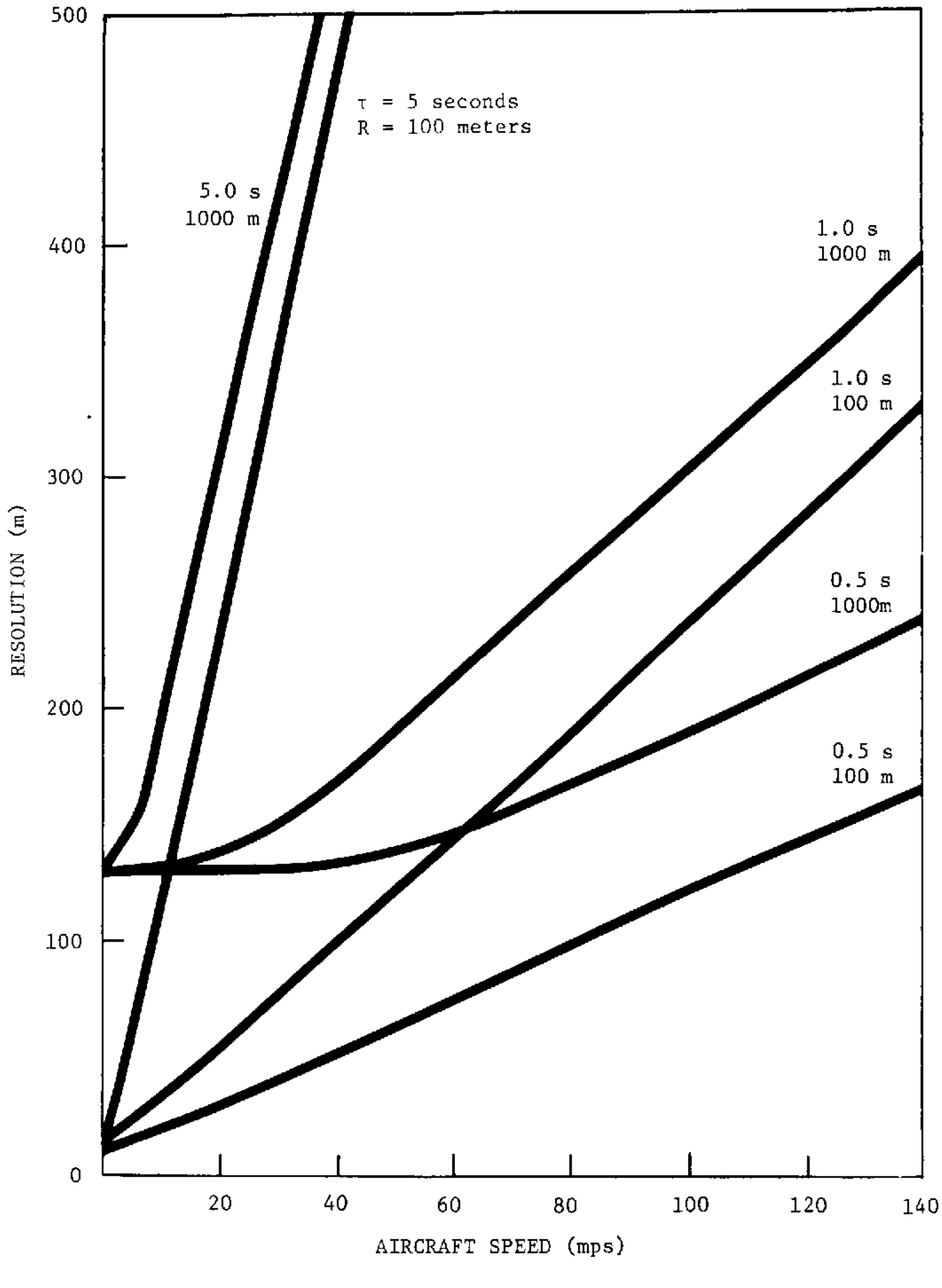


FIGURE 4-2
RESOLUTION OF THE GFCI SENSOR FOR VARIOUS VALUES OF TIME CONSTANT, AIRCRAFT SPEED AND ALTITUDE. THE FIELD OF VIEW IS FIXED AT 7.5°.

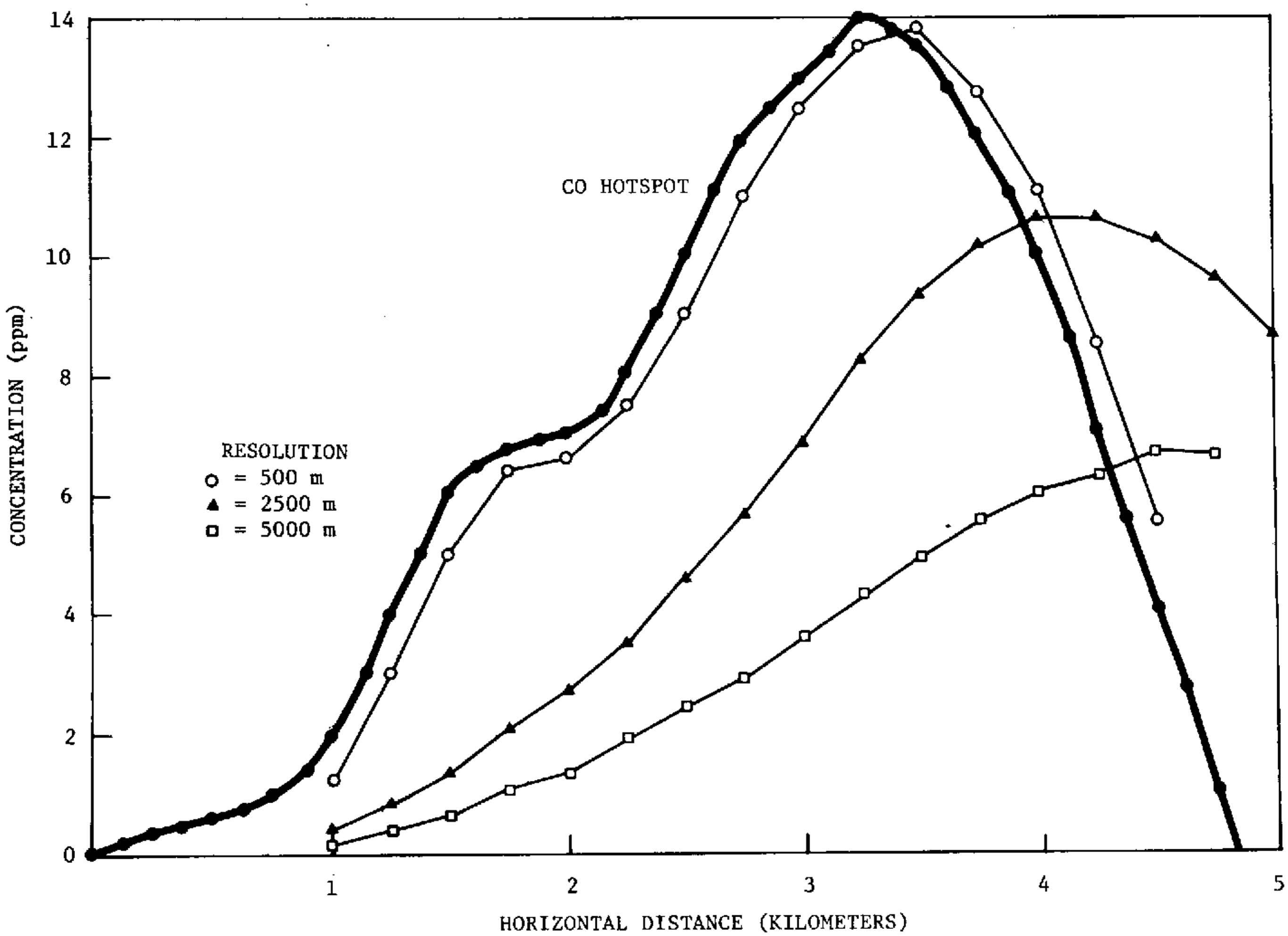


FIGURE 4-3
RESPONSE OF THE GGCI WHEN FLOWN OVER A TYPICAL CARBON MONOXIDE POLLUTION HOTSPOT

is no worse than that of the model. Therefore, the variations which occur on a smaller scale will not be detectable. This should be a consideration when comparing instrument performance with a distribution of pollution from APRAC.

4.2.3.2 Modified GFCI For SO_2 Detection.

- Operating principles

In virtually every respect, this instrument is identical to the one just described for CO. The only modifications are in the gas cell (which is filled with SO_2 instead of CO), the external optical filter and possibly the detector. Conversion of the CO unit to SO_2 detection is expected to take on the order of months.

Figure 4-4 illustrates the response of the modified GFCI unit to a localized source of SO_2 using a typical time constant and altitude combination. The SO_2 distribution has been extracted from a simulation of the Washington, D.C. area (June 8, 1972) using SCIM. The peak of the SO_2 curve occurs near the center of a smoke stack plume produced by the Potomac River (PEPCO) power plant in the Alexandria area of the city (see Figure 3-27).

- Performance

Although this instrument has not yet been built and tested, it is anticipated that longer time constants and poorer performance can be expected. The wavelengths of operation will be either 4.0 or 8.6μ.

4.2.3.3 MAPS.

- Operating principles

The MAPS unit utilizes the same physical principles in detecting pollutants as GFCI. The only major difference is that this is an advanced unit with the capability of detecting 6 gases at the same time. In addition

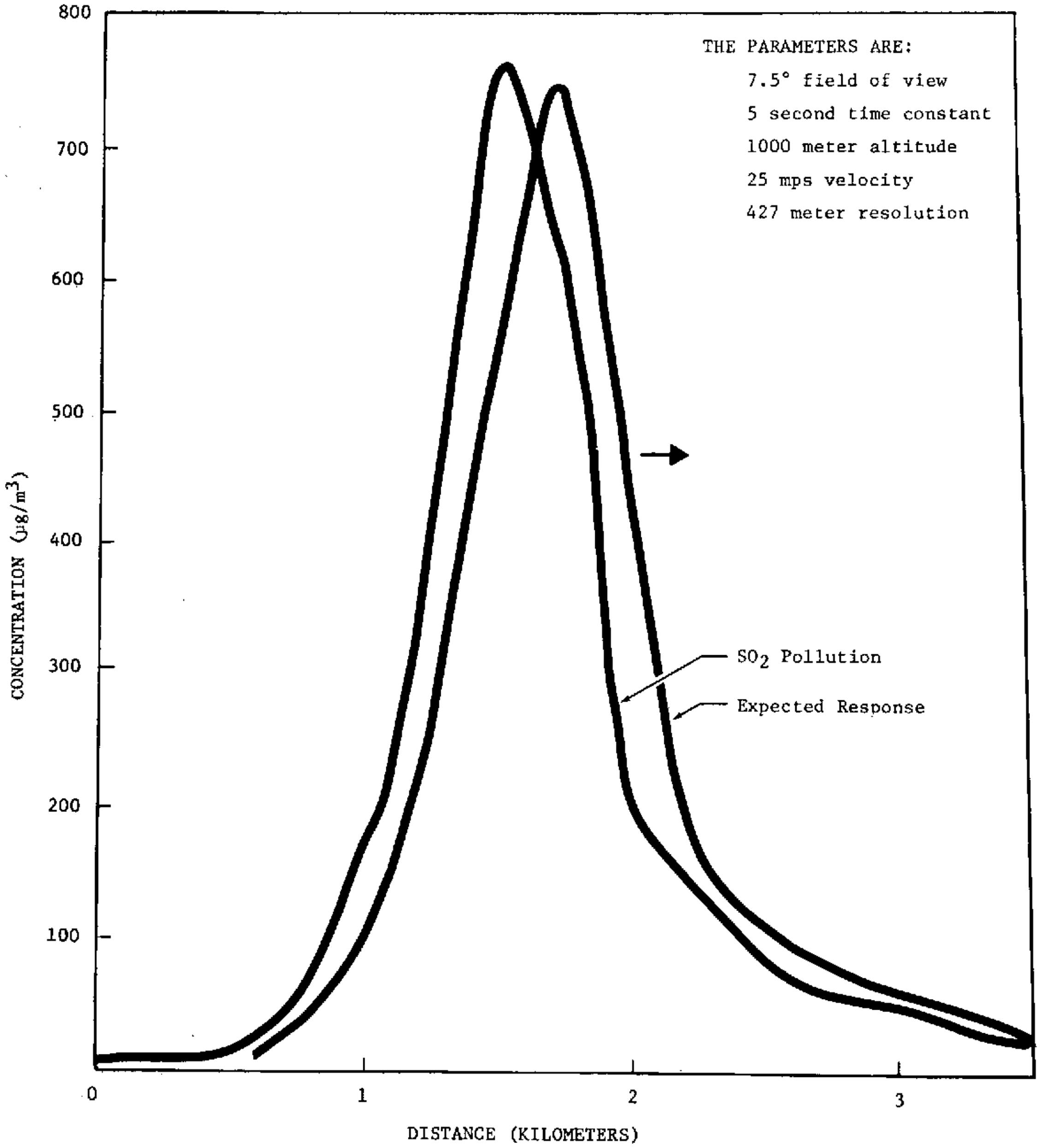


FIGURE 4-4
EXPECTED RESPONSE OF THE MODIFIED GFCI WHEN FLOWN OVER MODELED SO_2 POLLUTION IN THE DIRECTION SHOWN

the basic technique has been modified to eliminate the requirement of measuring the total background emission by using two sets of filter cells with the pollutant cell of each set having different concentrations of gas. In this way the variations in power level reaching the instrument can be corrected out of the final result. The MAPS instrument will also weight less than the GFCI instrument (68 kg). The power consumption of the MAPS unit will be 65 watts. For installation in RB57 aircraft a heater must be provided to maintain the temperature of the instrument. This heater will consume 100 watts. The MAPS unit will have more advanced design optics and temperature controlling mechanism for the built-in blackbody calibrator.

- Performance

The Table (4-2) which follows lists atmospheric pollutants under consideration, of which six will be chosen for detection:

Table 4-2

WAVELENGTH OF OPERATION AND ACCURACY
FOR SEVERAL CANDIDATE POLLUTANTS FOR MAPS

Materials	Accuracy	Min. Det. Conc.	Response Time	Dynamic Range
CO (4.6μ)	10%	-	1 second	0-3ppm
CO_2 (2.1μ)	1%	-	-	-
SO_2 (4.0, 8.6μ)	-	-	$\geq$1 second	-
NO_2 (3.3, 7.6μ)	-	-	-	-
NH_3 (3μ)	5%	-	-	-
CH_2O (3.5μ)	$\pm$2ppb	-	-	-
CH_4	-	-	-	-

MAPS References

1. NASA/LRC Staff. "Environmental Quality Enhancement Program Study", December 1972.

2. NASA/LRC Staff. "Environmental Quality Enhancement Programs and NIMBUS G Atmospheric Quality Measurements", February 1973.

3. NASA/LRC Staff. "Review of Langley Applications Activities for Associate Administrator for Applications", January 1973.

4. NASA/LRC Staff. "NIMBUS G Atmospheric Quality Experiments", August 1972.

5. NASA/LRC Staff. "The Atmospheric Quality Measurement Systems Program", March 1972.

6. NASA/LRC Staff. "Presentation of LRC Air Pollution Research Programs to the Office of Applications" February 1972.

7. Lawrence, J. and L. Keafer, Jr. "Remote Sensing of the Environment", presented to the Interagency Conference on Environment, Lawrence Livermore Laboratory, October 1972.

8. Keafer, L. Jr. and J. Kopia. "Development of Flight Experiments for Remote Measurement of Pollution", presented to the 2nd Annual Remote Sensing of Earth Resources Conference, March 26-27, 1973.

9. Science Applications Inc. Staff. "Monitoring of Air Pollution by Satellite (MAPS). Phase I", June 1973.

10. Convair Aerospace Division of General Dynamics Staff. "Development of the Gas Filter Correlation Instrument for Air Pollution Detection", GDCA-HAB-73-011, Final Report, August 30, 1972.

11. Convair Aerospace Division of General Dynamics Staff. "Informal Supplementary Flight Test Report", prepared under contract NAS1-10466.

12. Reichle, H. and H. Orr. Private communication at Langley Research Center, October 1973.

4.2.4 High Speed Interferometer (HSI)

- Operating Principles

The HSI is a remote sensing instrument which, as its final output, produces absorption or emission molecules in the atmospheric path being viewed by the instrument. The device operates as an interference spectrometer utilizing a unique laser-driven electro-mechanical stepping system which provides higher speed than in conventional interference spectrometers. Computerized processing of the resultant interferogram produces its Fourier transform--the spectrum. The spectrum must then be inspected to detect the characteristic lines of bands which identify the constituents in the atmospheric path observed by the instrument. There are two principal methods of observation: in the first, the atmospheric gases are observed in absorption at all wavelengths when the sun or artificial source is used directly as the radiation source; in the second, the observed spectrum appears in absorption and partly in emission when the instrument views the gases by the diffused reflected radiation from the earth's surface and/or clouds. The spectrum produced by the second method contains absorption features in the short wavelength region (less than 3μ) and the combination of absorption and emission features at the longer wavelengths; the degree by which the second type predominates depends upon the effective surface temperature relative to the atmospheric temperature.

In its use to date, observations have been made in both modes. For the observations considered in the context of this summary, however, measurements would be made in the "down-looking" mode, the second of those described above. In this case the energy levels being detected are considerably lower than for the direct solar case and the difference is reflected in the comments given against the operational description given in the following pages. It is perhaps worth mentioning that down-looking observations at very high spectral resolution in the infrared are difficult to perform so that the full energy gathering and information multiplexing advantages of the interferometric method must be utilized; this is the basis of the approach which led to the present HSI design.

The instrument is intended to carry out measurements to obtain an inventory of trace constituents (natural and pollutants) and to determine a "first-cut" indication of their global and regional variability. Since the observations are direct, the spectra can be interpreted with high quantititive accuracy, and the high spectral resolution allows relatively low concentrations to be detected. However, the instrument is not suited to, or intended for more detailed long-term monitoring of specific constituents, where an approach which achieves appropriate economy in recorded information is to be perfected.

The major advantage of this instrument is that it produces high resolution absorption spectra in the wavelength range covered by the detector. Therefore, it monitors the presence of each atmospheric constituent in its spectral range and is, as a result, more suited for identification of the presence of various constitutents, rather than the accurate determination of the actual concentrations.

A list of several pollutants which can be detected is given in Table 4-3 along with the wavelength of operation and the sensitivity expected.

TABLE 4-3

MINIMUM DETECTABLE CONCENTRATION OF VARIOUS ATMOSPHERIC CONSTITUENTS BY THE HSI FOR AN OPTICAL PATH OF 2 KM-ATMOS.

CONSTITUENT	WAVELENGTH (μ)	SENSITIVITY* (ppb)
CO	4.67	1.0
CO_2	4.26	0.2
NO	5.33	4.0
NO_2	6.18	0.4
N_2O	4.5	0.4
SO_2	7.34	3.0
HNO_3	7.56	<5.0
HCl	3.47	1.0
CH_4	3.31	2.0
C_2H_2	3.04	3.0
C_2H_6	3.35	2.0
H_2CO	3.59	1.0
O_3	4.74	50.0
H_2O	6.27	1.0
NH_3	2.99	1.0
H_2O_2	2.92	10.0

*Values given are for the down-looking mode for an aircraft altitude of 1 km assuming reflected solar radiation.

- Physical Properties and Power Requirements

Weight - Presently the unit and its support equipment weighs 1100 kilograms. A more advanced version is expected to weigh approximately 362.5 kg - distributed as shown below.

Optical Instrument	75
Recorder	22.5
Power Supply	100
Electronics	165
Total	362.5

Volume - The instrument itself is 0.6 meters on a side (0.21 cubic meters). The electronic instruments, power converters and regulators and tape recorder consume additional space.

Power - Surge power requirements are 4300 watts with an average of 2850 watts and an eventual average of 1500 watts expected. This is provided by 120 volt, 60 hertz, from a DC to AC inverter.

- Instrument Characteristics

Calibration - This is required infrequently and could be automated if required.

Drift - This represents a minimal problem and is concentrated mostly in the electronic system.

Cryogenics - Liquid nitrogen is used to cool the detector.

Field of View - To guarantee adequate signal levels, as well as minimizing simulation noise caused by rapid changes in the surface albedo during instrument down-looking observation, the field of view must exceed 1°.

Image Motion Compensation - This could be provided, if required, by addition of external optics. Such optics would take the form of a mirror designed to track a spot on the ground during the collection time (three minutes).

Operating Conditions - There are no serious temperature or humidity requirements.

Auxiliary Measurements - Temperature and humidity vertical profiles are required for complete mathematical analysis of the measured data.

Orientation - The aircraft-mounted HSI will be positioned to look vertically downward, although any orientation could be used.

Warm-up Time - The warm-up time is small (minutes).

- Performance

Atmospheric Species - The spectra obtained from observations will contain features of absorption bands of molecules in a wavelength range covering the molecular bands, provided that the absorption strengths times the relative atmospheric mixing of the species are adequate for detection. Table 4-3 is provided to give an idea of the molecules that can be detected for the minimum levels shown for an optical path of 2 km-atmos. More molecules than included in Table 4-3 may be detected by HSI.

Materials - The instrument will see any constituent which has absorption bands or lines in the wavelength range of the instrument (2-20μ). These include CO, CO_2, SO_2, NO, NO_2, HNO_3, HCI and others.

Accuracy, Minimum Detectable Concentration - See Table 4-3.

Lagtime - The lagtime is zero.

Collection Time - The interferogram is produced in 3 minutes for each column of air to be measured. This is the time required for a complete scan of the mechanical section of the interferometer.

Response Time - The 1/e time of the electronics is one second.

Dynamic Range - This is undefined for several gases but is expected to be several orders of magnitude.

- Data Handling

Analog or Digital - The instrument produces digital voltage signals which are recorded on digital tape.

Bits per Byte - 14 bits are used to format a byte.

Time per Reel - Each tape will accept up to 20 minutes of flight data.

Preprocessing - This is not required. The magnetic tape is computer compatible and is used directly.

CPU Time per Point - 91 seconds of computer time (using a Univac 1108) are required to invert the interferogram and have the computer plot the absorption spectrum.

Bit Rate - 5 kilobits per second are transferred from the HSI electronics to the magnetic storage tape for processing on the ground.

- Limitations

Atmospheric - Errors in the derived abundances of constituent gases or pollutants are minimized by monitoring the observed abundance of known species (such as CO_2), so that correction for the effects of scattering by smoke and particulates can be made.

Flight Plan - Since it takes 3 minutes to produce information on one column of air, the term flight plan as used for the other instruments really comments on a different type of constraint. See spatial resolution comments below.

Day/Night Operation - Operation of the system is possible during day or night conditions.

Vibration - Although this is an electro-mechanical device, vibration in the platform has not proven to be a problem.

RFI - This is not a major influence in the noise level of the data.

Smoke - Smoke and other particulates do limit system performance although the quantified influence is unknown.

Ground Pattern - This does not influence the data obtained because a radiometric channel corrects for changes in ground brightness.

Safety - No safety problems exist when using this unit.

Spatial Resolution

As mentioned, the long integration time of HSI would limit its application to those where a fixed platform is used or where the distribution of constituents is uniform over a large area. This is consistent with the conclusion that is not suited to be a mapping device, but rather an instrument for detecting the presence of various constituents so that more specialized instruments can be used.

Consider a sensor which "sees" to the ground and has a square footprint of side D. Several factors influence how quickly (or over what distance of travel of the platform) the sensor detects the changes in pollution concentration. These factors were shown in Section 4.2.3.1.

For this instrument, two regimes of resolution will exist. First, if the velocity of the aircraft is low, such that the footprint D exceeds the product of the velocity and the collection time, then the limit is D. If, however, V times (collection time) exceeds D, then that product is the resolution limit. Table 4-4 depicts the resolution of the HSI for various operating conditions.

TABLE 4-4

HSI RESOLUTION

VELOCITY, (mps)	RESOLUTION*, (m)
5	900
10	1,800
15	2,700
20	3,600
50	9,000
100	18,000

*Instrument is time constant limited for altitudes up to ~10km.

The resolution of the instrument appears to be greater than 100 meters for a wide range of operating conditions. This would appear to give inadequate resolution when compared with spatial variation predicted by models of SO_2 and CO distributions in the Washington, D.C. area.

HSI References

1. Farmer, C.B. et al, "Near-Infrared Interferometric Measurements of Stratospheric Composition to be made from the Concorde", Presented at Second Conference on CIAP (Climatic Impact Assessment Program) November 1972.

2. Farmer, C.B. "Global Survey of Atmospheric Trace Constituents and Pollutants", Final report to AAFE Program. May 1, 1973.

3. NASA/Langley Staff, "Environmental Quality Enhancement Program Study", December 1972.

4. NASA/Langley Staff. "Nimbus G Atmospheric Quality Experiments", August 1972.

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10. Farmer, C.B. "Minimum Detectable Relative Concentrations of Pollutants using the HSI in units of parts per billion", JPL Chart No. 325-980B.

11. Farmer, C.B. "Minimum Detectable Concentrations of Molecules in PPB", JPL Chart No. 325-981B.

12. Farmer, C.B. "High Speed Interferometer System for Airship", JPL report May 1972.

4.2.5 Lower Atmosphere Composition and Temperature Experiment (LACATE)[1]

- Operating Principles

The instrument built for the Lower Atmosphere Composition and Temperature Experiment (LACATE) is a multichannel infrared radiometer operating in the 6 to 18μ region. The instrument scans in the vertical by orienting the device to look horizontally through the earth's atmosphere toward the limb. The phenomenon observed in the experiment is the thermal IR emission coming from the planetary horizon. The horizon is scanned in the vertical to obtain measurements of radiance profiles in spectral regions characterized by strong absorption bands of the gases of interest. These radiance profiles are then mathematically inverted to obtain temperature as well as atmospheric and pollution constituents. As presently designed, limb radiance profiles can be measured as follows:

Band	Gas	Result
two 15μ bands	carbon dioxide	temperature
9.6μ	ozone	concentration
11.3μ	nitric acid	"
17.1μ	nitrous oxide	"
6.3μ	water vapor	"
7.78μ	methane	"
6.2μ	nitrogen dioxide	"
an interval centered at 10.8μ	aerosols	"

[1] References used in the LACATE analysis are listed at the end of this Section, 4.2.5.

Theoretically any gas having a strong absorption band in the 6 to 18μ region may be measured. Thus, it is possible to add additional channels to this instrument to measure sulfur dioxide or carbon monoxide.

As presently designed the instrument aboard a high flying aircraft will provide measurements which can be inverted into vertical profiles with accuracies and resolutions anticipated to be as follows:

Constituent	Accuracy	Approximate Vertical Resolution*
Ozone	± 10%	0.4 km at 10 km altitude
Water Vapor	± 10%	0.8 km at 10 km altitude
Nitric Acid	± 15%	0.4 km at 10 km altitude
Methane	± 13%	0.8 km at 10 km altitude
Nitrous Oxide	± 10%	0.8 km at 10 km altitude
Nitrogen Dioxide	1-2 ppb	0.8 km at 10 km altitude

The principal drawback to operation of the instrument from an aircraft platform is the need for a cloudless line of sight from the sensor to the edge of the atmosphere. In addition, water vapor absorption in the troposphere creates undesired opacity in many bands of interest. Thus, the instrument will have severely limited applicability in any aircraft program.

In the spacecraft configuration, the instrument can scan 80° in azimuth. This ability to scan is not critical to aircraft operation since the aircraft may be turned as a substitute for horizontal scanning.

*See discussion of vertical resolution at end of section.

The instrument as now designed is being constructed for operation from a high altitude balloon in the spring of 1974. Modification and adaptation of this instrument for aircraft use is further in the future.

- Physical Properties and Power Requirements

Weight - The total weight of the instrument with the solid cryogen cooler is 63 kg., distributed as follows:

radiometer and scan drive	18.1 kg
radiometer electronics	5.4 kg
interface electronics	5.4 kg
solid cryogen cooler	34.0 kg

Since the solid cryogen cooler may be replaced with a much smaller cooler for aircraft operation, the cooler weight should drop by at least 22.7 kg resulting in an overall weight of approximately 41 kg.

Volume - The instrument is basically cylindrical with a maximum of 0.25 m in diameter and a height of 1.25 m. With the solid cryogen cooler attached the volume should be less than 0.2 cubic meters. With a smaller cooler this volume could be reduced to 0.06 cubic meters. In addition to the instrument, there are two electronic boxes - the interface electronics and the radiometer electronics. Each of these boxes is 15 cm. by 20 cm. by 16 cm. and fit into standard equipment racks. This will add an additional 0.01 cubic meters to the volume.

Power - The total power is 45 watts average, with 0.5 second duration peaks of 60 watts if azimuth slewing is employed. The distribution of power is as follows:

Components	Peak	Average
radiometer & scan drive	22.0 watts	11.0 watts
radiometer electronics	19.0 watts	17.0 watts
interface electronics	19.0 watts	17.0 watts

Volts - 28 volt, DC from the aircraft electrical system will power the instrument.

- Instrument Characteristics

Calibration - The instrument has a hot inflight automatic calibrator on board.

Drift - Temperature can cause instrument drift but can be corrected if temperature variation is known.

Cryogenics - Liquid nitrogen is required to cool the detector to 77°K.

Personnel Required - The instrument has been designed and constructed for automatic operation with no personnel in attendance.

Field of View - 0.25 to 1 milliradian depending on spatial resolution of the gas of interest and signal/noise characteristics.

Scanning - The balloon borne version has a vertical scanning capability of 8°. The satellite designed version scans 4° in the vertical and ±40° in azimuth. There is no theoretical or practical limitation to scanning except that the detector should not point at the ground. When operating from a high altitude aircraft (e.g., 10 km) the scan would be from the horizontal to 4° downward only.

Operating Conditions - It is desired to maintain the instrument temperature within a range of 10°K. In addition, the temperature variation must be known to an accuracy of 10 millidegrees. Temperature changes effect the focus and focal point of the optics.

Auxiliary Measurements - The temperature profile from the ground to scanning altitude is required at some representative point between the detector and the edge of the atmosphere. The profile should be accurate to ±2°K. This is within the capability of standard Weather Service radiosondes.

Orientation - The instrument may be mounted with any orientation as long as the detector optics is not pointing toward the ground or directly at the sun.

Warm-up Time - Warm-up time for the instrument is very short. One-half hour is considered to be the absolute maximum.

- Performance

Materials - CO_2 (temperature), O_3, HNO_3, N_2O, H_2O, CH_4, NO_2, aerosols and others.

Accuracy - The accuracy of detection for each pollutant is expected to be within 15% of the concentration.

Resolution - See discussion of resolution at end of this section.

Minimum Detectable Concentration - The minimum detectable concentration for each pollutant is estimated to be in the parts per billion range.

Lagtime - The lagtime is approximately zero.

Collection Time - The balloon-borne instrument will take an 8° vertical scan in 32 seconds. The aircraft instrument will take a 4° vertical scan in 16 seconds. Each 4° scan consists of 160 data readout points occurring at 0.1 second intervals. Thus, the adjacent data points will overlap due to the 0.25 milliradian field of view and provide redundant data. The instrument scans continuously with micro-second response readouts occurring at each of these preselected points. Readings are taken during both the upward and downward scans. The cognizant scientist suggests that when operating at a 10 km altitude, every four adjacent data points should be stored, averaged and readout as one point to reduce data redundancy. Thus, one scan would yield 40 data points at 0.4 second intervals each.

Response Time - The instrument response is in the microsecond range.

Dynamic range - The dynamic range of the LACATE is a function of the gas measured and the spectral band used. Estimated values for the satellite designed version of the instrument are as follows:

Constituent	Maximum	Minimum
CO_2 (broad)	9.000 w/m^2-ster.	0.0043 w/m^2-ster.
CO_2 (narrow)	5.000 "	0.0038 "
O_3	2.700 "	0.0014 "
H_2O	0.2500 "	0.0007 "
HNO_3	0.4000 "	0.0007 "
Aerosols	0.4000 "	0.0007 "
N_2O	0.4000 "	0.0032 "
NO_2	0.0800 "	0.00073 "
CH_4	0.3500 "	0.0007 "

Altitude - The instrument has been designed for satellite application. The cognizant scientist has serious reservations about its operation from a platform within the atmosphere. No investigation of this operational mode has been conducted.

- Data Handling

Analog or Digital - The data is recorded digitally.

Time per reel - A 400 meter reel of digital tape will store more than 2 hours of continuous data.

Preprocessing - Preprocessing is required to reformat the digital tape into computer compatible form.

CPU time per point - A profile of 40 points required 2 seconds on a CDC 6600.

Bit rate - Based on data published for the spacecraft configuration the output data rate for aircraft operation can be estimated as follows. The data will consist of 4 12-bit channels sampled at 10 times per second and 6 12-bit channels sampled at half that rate which is equivalent to a total of 7 12-bit words sampled 10 times per second. With additional allowances for housekeeping the total data rate becomes approximately 1080 bits per second. During continuous operation this would yield somewhat less than 4 megabits per hour. If a tape recorder with a packing density of 280 bits per cm. (approximately 720 bits per inch) is used with a speed of 2.5 cm. per second, a 400 meter reel will store more than 2 hours of data.

- Limitations

Atmospheric – The LACATE instrument will not detect through clouds. Therefore operation must be on a cloudless day or limited to line of sight applications. The presence of water vapor in the scan path presents problems which in the long run may be insurmountable. Further laboratory studies of this problem must be made to determine the exact nature of the problem. It may be possible to obtain some results for selected absorption bands if the water vapor distribution in the path is measured. The following data extracted from the "Handbook of Military Infrared Technology" give some indication of the possibilities of measurement.

Band	Gas	Approx. Water Vapor Transmission
15μ	CO_2	0 *
9.6μ	O_3	40%*
11.3μ	HNO_3	25%*
17.1μ	N_2O	60%**
7.78μ	CH_4	near 0 *
6.2μ	NO_2	0 *
10.8μ	aerosols	40%*

*Path length 16.25 km, temperature 68°F, precipitable water 15.1 cm.

**Path length 0.3 km, temperature 56°F, precipitable water 2.2 mm.

These data show that there is partial transmission over reasonable path lengths in the ozone, nitric acid, nitrous oxide and aerosol absorption bands. If the water vapor in the path and its absorption characteristics are measured it may be possible to calculate the absorption due to the pollutant and thus calculate the column density of pollutant.

In addition to water vapor interference smoke particles and particulates in general interfere with the instrument reading. Further investigation of this is necessary.

Flight Plan - There are no restrictions on any flight plan as long as the sensor is looking away from the earth's surface and not looking directly into the sun. However a very sophisticated record of the platform navigation parameters would be required to utilize readings taken during platform turns, banks or other maneuvers. Thus this instrument would be best used in level and straight legs of any flight plan.

Day/Night - The instrument may operate at both times.

Vibration - As presently designed the balloon instrument cannot withstand vibration. However there is no theoretical reason why it could not be modified to withstand vibration. Laboratory shock mounting tests must be performed to determine the optimum mounting.

Radio Frequency Interference - RFI can affect the threshold measurement level. Further work is necessary to quantify this effect.

Ground Pattern - The ground pattern will saturate the detector necessitating a short recovery time. Therefore the upward scan cycle may be eliminated after the detector has looked at the ground.

Safety - Other than handling of cryogenic material the instrument poses no safety problem.

• Spatial Resolution

Since LACATE will be operated primarily in a horizontal looking mode spatial resolution must be discussed in terms of the horizontal and vertical resolution. The resolution is determined by the instrument's field of view plus any field masks.

Therefore resolution is strictly a geometrical problem. As presently configured the field of view is either 0.25, 0.5 or 1 milliradian depending on the pollutant to be studied.

The vertical resolution for tropospheric application may be estimated as follows. Assume that the bulk of the pollutant is trapped in a mixing layer approximately 1500 meters high. A LACATE instrument located at the surface looking horizontally would penetrate the top of the layer at a distance of about 150 km. With an instrument field of view of 0.25 milliradians the vertical resolution at 150 km would be about 35 meters.

If the instrument scans vertically at $\frac{1}{4}^{\circ}$ per second the four degree scan would take 16 seconds as stated previously in this section. For the case where 4 adjacent data points are combined to give one reading the effective field of view would be 0.25 milliradians plus the angle through which the instrument has moved during the 0.4 second interval. This would add an additional 1.75 milliradians to the effective field of view resulting in a net vertical resolution of 280 meters at a distance of 150 km.

The horizontal resolution is determined by the non-scanning field of view and is 35 meters at a distance of 150 km for a single microsecond response reading. However for an airborne platform moving at 31 meters per second (60 knots) the platform would move 12.5 meters during a 0.4 second scan and readout of 4 adjacent data points would have a horizontal resolution of 47.5 meters. A total 16 second scan would cover a horizontal distance of 531 meters.

LACATE References

1. NASA/LRC Staff. "Environmental Quality Enhancement Program Study," December 1972.

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4. NASA/LRC Staff. "NIMBUS G Atmospheric Quality Experiments," August 1972.

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8. Keafer, L., Jr. "Development of Flight Experiments for Remote Measurement of Pollution," Presented at the Second Annual Remote Sensing of Earth Resources Conference, March 1973.

9. Russell, J. "The Inference of Atmospheric Ozone Using Satellite Horizon Measurements in the 1042 cm^{-1} Band." Journal of Atmospheric Sciences, Vol 29, No. 3, March 1972.

10. Russell, J. Private communication, October 1973.

11. Wolfe, W. L. ed. "Handbook of Military Infrared Technology," Office of Naval Research, 1965.

4.2.6 Laser Radar (LIDAR)

- Operating Principles

In the optical and near IR, lasers have high power (~1 megawatt), high energy (~1 Joule/pulse) and short pulse duration (~3-50 nanoseconds). The detected signal is produced by the interaction of the laser pulse and material in the atmosphere. In aerosol detection schemes, the radiation scattered from these materials is recorded as a function of time which produces range/concentration profiles of high resolution since the pulses may be only a few meters long and may be sensitive to variations occurring over distances of that order. In this application, a variety of source wavelengths have been used including Ruby (0.6943μ), Nd:YAG or Nd:Glass ($1,06\mu$) or dye lasers (~ 0.4 to $\sim 1.0\mu$).

Active instruments avoid some of the basic limitations of passive instruments. The optical instruments give vertical and, if desired, horizontal profiles without complex mathematical techniques. Instruments are sensitive over the entire air path between transmitter and receiver.

The optical lidar unit of interest here is an adaptation from a four color dye laser designed for remote detection of algae. This instrument is to be used to detect aerosols and mixing height and will possibly measure the distribution of nitrogen in the atmosphere as a calibration technique. Future applications will utilize a single dye (Rhodamine 6G) operating at 0.59μ. The existence and airworthiness of the 4 color laser make it most attractive for the present work.

The distribution of nitrogen may be determined by using Raman scattering data. In this process, a very weak component of the detected radiation is shifted in wavelength ralative to the laser wavelength due to changes in energy within the vibrational levels of the molecule. These data may be used in lieu of local meteorological data to provide the vertical profile of atmospheric molecular density profile.

In addition, the aircraft may be flown at altitude such that the mixing layer is below the instrument. This would provide a clear air path down to the mixing layer which can be used as part of the calibration since it provides an approximate zero reference.

The final result will be a measure of the aerosol scattering relative to the scattering provided by the molecules in the atmosphere.

- Physical Properties and Power Requirements

Weight - The present unit and its electronics/data reduction package weigh about 315 kg. A newer single dye laser is expected to weigh 295 kg.

Dimensions and Volume - The laser and receiver optics are 0.5 x 0.7 x 2.2 meters (0.77 cubic meters). The electronics consumes half of a standard rack.

Power - The average power consumption of the system is 1 kilowatt. Reductions in consumption are expected to drop this figure to 600 watts. The standard aircraft power provided at 28 volts, DC drives the system, Power regulation would be advantageous since the analog to digital converter in the data handling section is sensitive to line voltage noise.

- Instrument Characteristics

Calibration - This is provided by the nitrogen profile discussed above (or density from a local meteorological station) and by the low aerosol level seen in a clear path above the mixing layer.

Drift - The major drift is caused by pulse to pulse variations in the laser output energy.

Cryogenics - None are required.

Operators - One operator is required although he need not be fully devoted to this instrument.

Field of View - The transmitter will produce a 10 milliradian beam. The receiver will view a 20 milliradian area co-aligned with the laser beam.

Scanning - Scanning could be provided if desired.

Operating Conditions - The only major restriction is that condensation be kept off of the optical surfaces.

Auxiliary Measurements - A vertical temperature and pressure profile is required for the data analysis if the induced Raman scatter by atmospheric nitrogen is not measured.

Orientation - Any orientation is allowed. Down-looking will be used in this case.

Warm-up - 5 minutes is adequate.

Availability - This has been estimated at 6 months.

- Performance

Materials - This device measures relative aerosol content and the mixing height.

Accuracy, Minimum Detectable Signal - Theoretically, the mixing height altitude can be measured to within the length of a laser pulse (~100 meters). However, the instrumentation in its present form can only resolve the backscattered pulse into 20 parts. Thus for longer range experiments (higher altitude) the resolution is degraded.

Aerosol measurements will be made on a relative scale so accuracy or resolution are not well defined terms. The minimum detectable concentration has been suggested to be one particle/cubic centimeter.

Lag Time, Collection Time - These are both zero.

Response Time - The response time is limited by detector and electronics speed to 100 nanoseconds.

Dynamic Range - The system includes an 80db (10^4) logarithmic amplifier so that the dynamics range is quite large.

Altitute - In order to provide that a part of the path includes a region of clean air, the altitude should be in the order of twice the mixing height. This clean air region aids the calibration process.

- Data Handling

Analog or Digital - The output data are in the form of digital voltage levels stored on digital magnetic tape.

Preprocessing - Not required.

CPU Time per Point - 20 seconds of CPU time are required to analyze a single return on a state of the art general purpose computer.

Bit Rate - Approximately 4 kilobits are recorded on the magnetic tape.

The general philosophy of the data analysis is to first get the laser backscatter. Meteorological sources or Raman scatter data from nitrogen provide information on the local vertical profile of molecules in the atmosphere. Dividing the two profiles and correction for R^2 losses in the backscatter provides the relative aerosol to molecules scattering profile. Positioning is provided by aircraft navigational aids. Correlation calculations on successive data profiles can provide vertical and horizontal wind velocities.

- Limitations

Atmospheric/Meteorologic - Clouds, fog, haze and any other optical obstruction will limit the useful range of the sensor obstruction. This can be useful, however, since this provides ranging information which can be used in other experiments.

Flight Plan - The plane should not fly in its own wake.

Day/Night - Day or night operation is possible with higher noise levels in daylight. Raman spectra will be difficult to obtain during daylight hours.

Vibration - This poses no problem.

RFI - The capacitive discharge in the laser system tends to produce RFI in the data logging set. This problem appears to be solvable.

Smoke/Clouds - As mentioned, these can limit the useful range of this instrument but their range can be inferred from the data obtained.

Safety - Since this is an active device safety considerations do come into play. The suggested* standard of safety for the daylight adapted eye is 5×10^{-7} j/cm^2. The typical dye laser produces around 300 millijoules. If the device is at an altitude of 1000 meters and has a beam spread of 10 milliradians, the energy density will be 3×10^{-7} j/cm^2 which would present a health hazard. Of course, this calculation does not consider the influence of absorption or scattering within the optical path. In any case, precautions must be taken to guarantee that dangerous radiation does not reach the ground, especially at night since the dark adapted eye is much more susceptible to damage. Increase in the beam divergence or altitude of the aircraft could be used to avoid this danger.

- Spatial Resolution

Due to the narrow beam spread and high speed electronics of the LIDAR instruments, its resolution is expected to be on the order of tens of meters. This should be more than adequate to allow comparison of the modeled data for the Washington area to measured values of particulate and other constituents detected by LIDAR and in situ sensors.

However, safety considerations may require larger beam spread in the laser beam which will increase the ground spot. This is still not expected to degrade instrument resolution to a level comparable to that of the model (on the order of 100 meters).

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*See references at end of this Section, 4.2.6.

LIDAR References

1. NASA/LRC Staff. "Environmental Quality Enhancement Study," December 1972.

2. NASA/LRC Staff. "Review of Langley Applications Activities for Associate Administrator for Applications", January 26, 1973.

3. NASA/LRC Staff. "Presentation of LRC Air Pollution Research Programs to the Office of Applications," February 1, 1972.

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6. Melfi, H. et al. "Airborne Laser Radar Studies of the Lower Atmosphere," NASA-TN-D-5558, December 1969.

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4.2.7 Airborne Contact Sensors

As stated in Section 4.0, one of the six airborne sensors originally proposed for analysis was the in-situ sampler commonly called "grab sampler." The grab sampler is defined in this study as any one of a generic class of sensors which collect a sample of air in some type of container for later analysis, either at the location where sampled or in a laboratory located elsewhere. In the NASA airborne program, grab sampling will specifically refer to the collection of air samples in containers on board the platform with subsequent analysis at some later time in a ground laboratory.

The initial analysis focused on the NASA/LRC system being developed under the cognizance of Dr. H. Reichle. After initial study of this system was completed, it was decided to analyze other in-situ systems for possible inclusion in the NASA airborne program. Three other systems were selected for analysis.

- The grab sampling being developed by NASA/LRC for monitoring of launch vehicle exhausts at Cape Kennedy. (This system will be called the NASA/Cape Kennedy grab sampler in this report).
- The grab sampling system used in the Los Angeles Regional Pollution Project (LARPP) by EPA personnel and contractors.
- The airborne contact sensor system used in LARPP and scheduled for operation in the St. Louis Regional Air Pollution Study (RAPS).

Airborne grab sampling systems in general consist of three functional parts.

- Ducts to guide the air sample from the outside into the desired location on the platform.
- A pump or other mechanism to draw in an air sample when required.
- A container for storing the air sample.

The principal difference encountered among the three grab sampling systems analyzed lies in the storage container used. The NASA/LRC system has attempted to use stainless steel storage bottles for sample storage, while the NASA/Cape Kennedy system uses glass bottles. In contrast to these two rigid containers, the LARPP system has employed inflatable polyethylene bags.

In general, airborne grab samplers suffer from two serious problems. The first is the uncertainty in determination of exactly what air sample has entered the storage container. The second is the change which occurs in the air sample before its extraction from the storage container for analysis.

This latter problem is particularly important in air quality sampling where the concentrations of the pollutant gases are small. Both the NASA/LRC and NASA/Cape Kennedy system personnel report serious difficulties with sample storage. Experiments have been conducted by the NASA/LRC personnel in which known concentrations of CO, on the order of a few parts per million, have been introduced into stainless steel storage bottles. After a few days of storage, the CO in the bottle has become completely undetectable. Similar problems are reported by the NASA/Cape Kennedy system personnel.

The grab sampling system used by NERC/Las Vegas personnel in the LARPP study employed polyethylene bags for sample storage. The air samples were stored for several hours before analysis in the ground laboratory for carbon monoxide and hydrocarbons. LARPP personnel have expressed confidence that the polyethylene bags store the air sample without significant change. However, they have not made any studies to verify their confidence.

In view of this continuing uncertainty over the validity of grab sample system results, it was decided to investigate other types of in-situ contact sensors as possible substitutes. A preliminary survey of such sensors and airborne systems utilizing these sensors revealed that a relatively complete airborne contact sensor system was being used by the Los Angeles Regional Pollution Project. In addition, the LARPP airborne system is being modified for use in the St. Louis RAPS program. The remainder of this section will describe the EPA/LARPP system and the modifications planned for the RAPS program.

The basic objective of the LARPP project was to measure the time variation of pollutants over the Los Angeles Basin. The heart of the pollutant sampling system consisted of two Bell 212 helicopters on lease from Petroleum Helicopters, Ltd., Fayetteville, La. These helicopters were specially instrumented for the present operation as described later in this section. The basic characteristics of the helicopter are described in Section 6.1.

All information pertinent to the LARPP project and the subsequent use of the modified LARPP helicopter system in the RAPS project was obtained from Evans[1,2] of NERC/Las Vegas who is the principal scientist for the project.

Table 4-5 shows the various specifications for the instruments planned for use in the RAPS version of the LARPP helicopter system. All of the instruments shown except the individual particle counter and the flame photometric SO_2 sensor were used in the original LARPP system.

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[1] Evans, R. B., "Aerial Air Pollution Sensing Techniques.", presented at the Second Conference on Environmental Quality Sensors, Las Vegas, Nevada, October 1973.

[2] Evans, R. B., private communications, October 1973.

TABLE 4-5
LARPP AIRBORNE INSTRUMENT SPECIFICATIONS

PARAMETER	MEASUREMENT METHOD	INSTRUMENT MANUFACTURER/MODEL	INSTRUMENT RANGES	MINIMUM DETECTABLE CONCENTRATION	LAG TIME & RESPONSE TIME	# OF DIGITAL CHARACTERS IN MAGNETIC TAPE OUTPUT	CALIBRATION METHOD	CALIBRATION CONCENTRATION	SAMPLING FLOW RATE	WARM-UP TIME	POWER CONSUMPTION
Fluorescent Particles	Fluorescence	Mee Industries/110	Continuous, 1, 2, 5, and 10 second intervals		250 ms Response Time (RT) per particle	4	Zero Output for zero source		2.75 l./sec	<30 sec	24-32 VDC. 560 W
Particles >0.3μ	Individual Particle Counter	Royco/220	10 channels			20	Internal calibration or latex particles of known size		31.1 l./min	<30 sec	115 VAC. 150 W
Visibility	Light scattering	MRI/1550B	Three Ranges	$b_{scat} \approx 0.1$	Variable R.T. 0.1 - 200 sec	6	Internal calibration or Freon 12	Pure Freon	283 l./min	15 minutes when relative humidity > 60%	115 VAC. 70 W Heater - 105W
NO	Chemiluminescent	Thermo Electron Corp./14B	0.05, 0.1, 0.25, 0.5, 1.0, 2.5, 5.0, 10 ppm full scale	0.0005 ppm	<2 sec with modifications (manual mode)	6	Sample gas	1 ppm NO in N_2	14-56.6 l./min	1 - 2 hours	115 VAC. <150 W Pumps - 475 W
NO_x	Chemiluminescent	Thermo Electron Corp./14B	0.05, 0.1, 0.25, 0.5, 1.0, 2.5, 5.0, 10 ppm full scale	0.0005 ppm	<2 sec with modifications (manual mode)	6	Bendix Calibration Inst.		14-56.6 l./min	1 - 2 hours	115 VAC. <150 W Pumps - 475 W
Ozone	Chemiluminescent	REM/612B	0-200 pphm 0-20 pphm 0-2 pphm	0.1 ppb	<1 sec	4	Internal Calibration	1/3 of full-scale reading	1 l./min	15-30 min	115 VAC. 55 W
CO	NDIR (Fluorescence)	Andros 7000	20, 50, 100, 200 ppm	0.1 ppm	6 sec < R.T. < 10 sec	6	Sample Gas	10ppm CO in N_2	1-2 l./min	30 min	115 VAC. 175 W
SO_2	Flame Photometric	Meloy SA 160	10 ppm	0.005 ppm SO_2	15 sec lag time <30 sec response time	6	Internal Calibration or Sample Gas	0.1ppm SO_2 in air			115 VAC. 500 W
Non-methane and Total hydrocarbons	PID	MSA 11-2	0-5 ppm 0-20 ppm	50 ppb	20 second lag time 15 second response time	6 6		10ppm C_3H_8 in N_2 10ppm CH_4 in air	2.l./min		115 VAC. 250 W Warm-Up - 1000 Watts
Temperature	Thermoelectric	Cambridge Systems Mdl 137-CI-SIA-TH				6			152 m/min or greater	5-10 min	115 VAC. 30 W
Dew Point	Thermoelectric	Cambridge Systems Mdl 137-CI-SIA-TH				6			152 m/min or greater	5-10 min	115 VAC. 30 W
Altitude	Pressure	Computer Instrument Corp. Mdl 8000	0-9.1 km	±12.2 m to 6.1 km ±0.4% above 6.1 km	±6.1 meters dynamic error	6	Airport Altitude				28 VDC.

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The selection of the air parcel to be studied was made each day by reviewing the local meteorology and analyzing the Los Angeles upper air sounding. When each day's study began, a cluster of three tetroons was released and set to float at one-half the inversion height. A third helicopter was used to release fluorescent particles near the cluster as an additional aid in tracking. The pollutant-measuring helicopters flew a square pattern along the edge of the parcel. Traverses were made at four levels. The first was at the inversion base and the last at 60 meters altitude at a sufficient clearance above ground obstructions. The remaining two levels are selected to divide the parcel into three equal altitude segments.

Instrument interrogation is once every six seconds with each instrument interrogated consecutively. Since ten on-board instruments were used, this would require 60 seconds for one data cycle.

All navigation was done by radar tracking of a transponder on each helicopter. The ground radar personnel radioed the location to the helicopter and the instrument operator recorded it on the magnetic tape recorder by using a set of thumb wheel indicators. This system has considerable potential for navigation error due to the time lag between the radar tracking and the insertion of the data on the tape. Ground support measurements included standard surface meteorological data and upper air sounding data. In addition, all data measured by the Los Angeles Air Pollution District were obtained. The project itself operated one instrumented van, which took air quality measurements at selected locations on the ground.

The LARPP helicopter required one instrument operator on board and seven or eight ground support personnel. It was estimated by NERC/Las Vegas that a similar number would be required to conduct a similar one-helicopter study.

NERC began preparation and instrumentation of the helicopters approximately one month prior to field usage. They estimate that 2.5 man years of time were used in this effort. This included 1 year of professional time and 1.5 years of technical time. The instrument and data package for each helicopter is estimated to have cost $100,000.

5.0 PAYLOAD DESCRIPTIONS

Based on information presented in Section 4 four potential remote sensing systems are described below. Many other combinations of sensors are possible but these four are considered as appropriate examples which can be used in future planning and studies.

The first system consists of the assembly of the six experiments initially suggested for the study, HSI, LACATE, MAPS, LIDAR, CIMATS and Grab Sampler. This system is called the initial summation payload and is labeled number 1 in Table 5-1 which shows the payload summations. The approach to this summation was to consider each experiment as a separate entity and to total the values for each parameter including instrument operators. The instrument operators required for each sensor are shown in Table 5-2. In the initial summation neither of the two crew members allotted for piloting large platforms and most small platforms was considered to be available for instrument operation. Thus the total initial summation would require six instrument operators plus two crew members. The second system shown in Table 5-1 is the initial summation payload plus the LARPP sensor package and one additional instrument operator.

System 3 has been called the slightly integrated payload. In this case the basic experiments summed in system 1 were inspected to see where obvious equipment redundancy could be eliminated or decreased. The most important changes are in automation of systems wherever possible and the integration of all data recording functions into one overall

TABLE 5-1

PAYLOAD SUMMATIONS

Type of Payload	Weight, kg	Volume, m^3	Power, w
1. Initial			
Sensors	893.0	1.26	2670
Personnel	540.0	3.00	-
Total	1433.0	4.26	2670
2. Initial plus LARPP			
Sensors	2028.0	4.96	5845
Personnel	630.0	3.50	-
Total	2658.0	8.46	5845
3. Slightly integrated			
Sensors	824.9	1.17	2430
Personnel	90.0	0.50	-
Total	914.9	1.67	2430
4. Slightly integrated plus LARPP			
Sensors	1937.2	3.76	5535
Personnel	180.0	1.00	-
Total	2117.2	4.76	5535

TABLE 5-2

REMOTE AND CONTACT SENSOR OPERATING PERSONNEL

Sensor	Present	Possible Future
CIMATS	2 full time	automatic
MAPS	1 part time*	automatic
HSI	2 full time	automatic
LACATE	automatic	automatic
LIDAR	1 part time	1 part time
Grab Sampler	1 full time	1 part time
SUB-TOTALS	6 full time	2 full time**
LARPP Sensors	1 full time	1 full time
TOTALS	7 full time	3 full time***

* Part time assumed one half full time.

** Four automatic sensors assumed to require one full time monitor.

*** On small platforms second crew member may serve as one of the instrument operators.

data recording system. Automation reduces the number of instrument operators from 6 full time to 2 full time and a further assumption was made that the second crew member on small helicopters and small fixed wing aircraft could serve as one of the instrument operators. Thus the net requirement for instrument operators is one full time which reduces the payload allowance for personnel from 540 kg to 90 kg. A standard weight of 90 kg is allotted for each person. In addition the cabin space for 6 personnel is assumed to be a minimum of $3.0m^3$. This reduces to $0.5m^3$ for one person. A space of $0.5m^3$ was allotted for each instrument operator. This assumes the operator is seated in a chair which is included in the volume. No allowance was made for additional space for operators to move about the cabin or for in flight access to instruments. Although both of these factors are important not enough data was available to justify an estimate.

System 4 is the slightly integrated payload plus the LARPP sensor package and one additional instrument operator.

Tables 5-3, 5-4, and 5-5 summarize the weight, volume and power specifications used in the summations.

Operation of any or all of these four systems was used as the basic goal in the platform analysis contained in the following section.

TABLE 5-3

REMOTE AND CONTACT SENSOR WEIGHT SPECIFICATION, KILOGRAMS

Sensor	Instrument	Electronics	Power Supply	Data Recorder	Cooler	Total Sensor Weight	*** Personnel	Total Weight
CIMATS	15.9	13.6	0*	E22.7**	-	52.2	180	232.2
MAPS	← 68.0 →		0*	E22.7	-	90.7	45	135.7
HSI	74.8	167.8	104.3	22.7	-	369.6	180	549.6
LACATE	18.1	10.9	0*	E22.7	11.3	63.0	0	63.0
LIDAR	← 272.1 →		0*	E22.7	-	294.8	45	339.8
Grab Sampler	← E22.7 →		0*	-	-	22.7	90	112.7
SUB-TOTALS						893.0	540	1433.0
LARPP Sensors	← 1135 →					1135.0	90	1225.0
TOTALS						2028.0	630	2658.0

*Instrument operates directly from aircraft 28V/DC current, no weight.

**E = estimate

***Standard weight allowance for one crew is 90 kg; 45 kg used for half time operator.

TABLE 5-4

REMOTE AND CONTACT SENSOR VOLUME SPECIFICATIONS, CUBIC METERS

Sensor	Instrument	Electronics	Power Supply	Data Recorder	Cooler	Total Sensor Volume	Personnel*	Total Volume
CIMATS	← 0.11 →		-	E0.03**	-	0.14	1.0	1.14
MAPS	0.34	0.01	-	E0.03	-	0.38	0.25	0.63
HSI	0.23	E0.04	E0.02	E0.03	-	0.32	1.0	1.32
LACATE	0.06	0.01	-	E0.03	***	0.10	0	0.10
LIDAR	0.17	E0.01	-	E0.03	-	0.21	0.25	0.46
Grab Sampler	← E0.11 →		-	-	-	0.11	0.5	0.61
SUB-TOTALS						1.26	3.00	4.26
LARPP Sensors	← E3.7 →					3.70	0.50	4.20
TOTALS						4.96	3.50	8.46

*0.5m^3 minimum space allocation for one operator and chair.

**E = estimate

***Cooler volume included in instrument.

TABLE 5-5

REMOTE AND CONTACT SENSOR POWER SPECIFICATIONS

Sensor	Instrument and Electronics	Data Recorder	Total
CIMATS*	30w/1.07 amps[2]	E80w/2.86 amps	110w/3.93 amps
MAPS*	65w/2.32 amps	E80w/2.86 amps	145w/5.18 amps
HSI**	←1500w/76.7 amps→		1500w/76.7 amps
LACATE*	45w/1.6 amps	E80w/2.86 amps	125w/4.46 amps
LIDAR*	600w/21.5 amps	E80w/2.86 amps	680w/24.36 amps
Grab Sampler*	60w/2.14 amps	-	60w/2.14 amps
SUB-TOTALS			2670w/116.77 amps
LARPP Sensors[1]			3175w[1]/113.40 amps
TOTALS			5845w/230.17 amps

*Instrument and recorder operate on 28V/DC

**Instrument and recorder operate on 120V/60 cycle AC; conversion from 28V/DC made at 70% efficiency

1. Peak output 4175 watts; figure shown is average. LARPP sensors operate on either 28V/DC or 600 cycle AC.

2. All amperages shown are for 28 volt DC equivalent.

6.0 PLATFORM ANALYSIS

An analysis of selected airborne platforms was performed with the objective of identifying any specific or generic platform which would be suitable for operation with the payloads described in Section 5.0. The analysis focused on particular fixed wing platforms which are currently associated in some manner with air monitoring but also included analysis of generic types of helicopters judged to be suitable.

Those specific platforms analyzed included the following:

Helicopters

Agency	Make & Model
NERC/Las Vegas	Bell 212 (leased for LARPP)
NERC/Las Vegas	Bell UH - 1 (H)
NASA/Wallops	Bell 204B
NASA/LRC	Bell 204
NASA/LRC	Sikorsky S-58 (leased)

Fixed Wing, Propeller

NERC/Las Vegas	Grumman OV-1B (Mohawk)
NERC/Las Vegas	Grumman OV-1C (Mohawk)
NERC/Las Vegas	Douglas B-26 (Monarch)
NERC/Las Vegas	Cessna C-45
California Air Resources Board	Fairchild Hiller M473 (C-123)
NASA/Wallops	Douglas C-54 (Tail No. 438)
NASA/Wallops	Beechcraft Queen Air

Fixed Wing, Propeller (Cont'd)

NASA/Ames	Cessna 402
NASA/Johnson	Lockheed NP-3A Electra (ES-1)
NASA/ Johnson	Lockheed NC-130B Hercules (ES-2)
Meteorology Research, Inc.	Cessna 206
Battelle Northwest, Inc.	Cessna 411

Fixed Wing, Jet

NASA/Johnson	General Dynamics WB-57F (ES-3)
NASA/LRC	General Dynamics RB-57

The following sections will present information on the specifications of general examples of these platforms and other appropriate platforms. In addition information is presented on other general factors such as air traffic control regulations and generalized operation costs.

6.1 Platform Specifications

This section presents specifications and associated information for all generic types of platforms shown above plus selected other generic types judged to be appropriate. Although most of the data shown are precise, sufficient approximations exist to warrant a caution against applying the data to a specific aircraft without further validation.

6.1.1 Performance Parameters and Cabin Dimensions

Table 6-1 lists the performance parameters and general cabin dimensions for all generic types of platforms analyzed. The data are considered self-explanatory except as discussed below. Unless

TABLE 6-1
PLATFORM PERFORMANCE SPECIFICATIONS AND CABIN DIMENSIONS

Manufacturer's Designations	Other Designations	PAYLOAD (Kg.) Including Fuel	PAYLOAD (Kg.) Excluding Fuel	RANGE (Km.)	SPEED (mps) Max.	SPEED (mps) Cruise	SPEED (mps) Stall	MAXIMUM ALTITUDE (meters)	CABIN OR COMPARTMENT No.	LENGTH (meters)	WIDTH (meters)	HEIGHT (meters)	VOLUME (cu. meters)	DOOR HEIGHT (meters)	DOOR WIDTH (meters)
HELICOPTERS															
ARDC/Brantly	305	410*	318*	354	54	49	0	3660	C1	2.3	1.39	1.22	3.90	0.82**	1.02
		* one crew							C2	-	-	-	0.47	0.30	0.69
														** Passenger Doors	
Bell 47 Series	47G-3B-2	300	-	402	47	37	0	5365	C1	1.5	1.52	1.37	3.12	est 1.2	est 1.5
	47G-4A	322	-	416	47	40	0	3415	C1	1.5	1.52	1.37	3.12	1.2	1.5
	47G-5	360	-	411	47	38	0	3200	C1	1.5	1.52	1.37	3.12	1.2	1.5
	OH-13S	113	-	402	47	37	0	5640	C1	1.5	1.52	1.37	3.12	1.2	1.5
	TH-13T	91*	-	402	47	37	0	5120	C1	1.5	1.52	1.37	3.12	1.2	1.5
		* one crew only													
Bell 206 Series	TH-57A	534	312	564	65	61	0	5395	C1	2.13	1.27	1.28	3.46	est 1.5	est 0.8
	OH-58A	534	312	564	65	61	0	5395	C2	-	-	-	0.45	-	-
Bell 204 Series	UH-1C	1375	-	615	66	64	0	3500	C1*	2.59	2.39	1.47	9.10	est 1.24	est 1.88
	204B	est 1362	-	est 615	66	64	0	est 3500	C2*	-	-	-	0.85	-	-
	UH-1E	1381	-	460	72	62	0	6400							
	UH-1F	1859	-	566	51	est 48	0	3780							
	TH-1F	1859	-	est 570	51	est 48	0	est 3780							
	HH-1K	1236	-	510	64	est 60	0	3110							
	TH-1L	1296	-	510	64	est 60	0	3110							
	UH-1L	1170	-	510	64	est 60	0	3110	*Data for 204B model is assumed to be similar in other models						
Bell 205 Series	UH-1D	1887	1239	511	55	55	0	3840	C1	2.34	2.44	1.24	7.08	1.24	1.88
	UH-1H	1872	1223	511	55	55	0	3840							
Bell 205A-1 Series	-	1823	-	500	55	55	0	4480	C1	2.34	2.44	1.24	2.08	1.24	1.88
Bell 212 Series	UH-1N	1647	-	476	54	est 54	0	3505	C1	est 1.22	est 2.45	est 1.25	est 3.7	est 1.24	est 1.88
Bell 209 Series	AH-1G	1363	-	622	98	est 75	0	3870	C1	est 2.6	est 2.4	est 1.5	est 9.0	est 1.24	est 1.88
	AH-1J	1224	-	622	98	est 75	0	3870	C1	est 2.6	est 2.4	est 1.5	est 9.0	est 1.24	est 1.88
Boeing-Vertol 107	107-II	3570	-	175	75	67	0	3960	C1	7.37	1.83	1.83	24.69	1.60	0.91
	CH/UH-46A	3898	-	370	71	67	0	3960	C1	7.37	1.83	1.83	24.69	1.60	0.91
	CH/UH-46A	4324	-	383	74	72	0	4265	C1	7.37	1.83	1.83	24.69	1.60	0.91
	Basic 107-II	4271	-	1020	62	62	0	4265	C1	7.37	1.83	1.83	24.69	1.60	0.91

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TABLE 6-1 (CONTINUED)

Manufacturer's Designations	Other Designations	PAYLOAD (Kg.) Including Fuel	PAYLOAD (Kg.) Excluding Fuel	RANGE (Km.)	SPEED (mps) Max.	SPEED (mps) Cruise	SPEED (mps) Stall	MAXIMUM ALTITUDE (meters)	CABIN OR COMPARTMENT No.	CABIN OR COMPARTMENT LENGTH (meters)	CABIN OR COMPARTMENT WIDTH (meters)	CABIN OR COMPARTMENT HEIGHT (meters)	CABIN OR COMPARTMENT VOLUME (cu. meters)	DOOR HEIGHT (meters)	DOOR WIDTH (meters)
Boeing-Vertol 114 Chinook	CH-47A CH-47B CH-47C	2542 3086 5921	- - -	370 346 370	66 79 78	66 72 71	0 0 0	3625 4570 4570	C1*	9.20 *Main cabin has a front passenger door and rear ramp	2.29	1.98	41.7	1.68* 1.98*	0.91* 2.31*
Enstrom T-28		274	-	531	57	49	0	4575	C1* C2 *2 Cabin Doors	1.52 -	1.63 -	1.27 -	2.70 0.20	1.22* 0.53	0.94* 0.44
Fairchild Hiller FH-1100		434	-	560	56	54	0	4325	C1* *2 Cabin Doors	2.35	1.31	1.40	4.31	est 1.5*	est 0.75*
Hughes Model 300	TH-55A 300	202 225	- -	328 480	38 39	33 35	0 0	3625 3960	C1* C1* *2 Cabin doors	1.40 1.40	1.30 1.30	1.32 1.32	2.40 2.40	1.12* 1.12*	0.81* 0.81*
Hughes Model 300C		128	-	410	46	44	0	4023	C1* *2 Cabin doors	1.40	1.30	1.32	2.40	1.09*	0.97*
Hughes Model 500	OH-6A 500 500M	353 485 503	- - -	611 606 589	66 67 67	59 61 61	0 0 0	4815 4390 4390	C1* C2*	2.44 *4 doors to cabin area, 2 C1 and 2 C2 types	1.37	1.31	4.38	1.19* 1.04*	0.89* 0.88*
Kaman Seasprite	UH-2A UH-2B UH-2C HH-2C HH-2D	918 971 983 1825 1039	- - - - -	1080 1080 685 632 685	71 71 69 68 74	67 67 67 67 67	0 0 0 0 0	5300 5300 5610 3750 5365	C1*	est 9.0 *4 doors to cabin area, 2C1 and 2C2 types	est 2.3	est 2.0	est 40.0	est 1.7* est 1.7*=	est 0.7* est 1.2*
Kaman K-700		1270	-	674	62	51	0	5545	C1* *2 Cabin doors	est 9.0	est 2.3	est 2.0	est 40.0	est 1.7*	est 0.7*
Kaman K-800		2230	-	1247	110	95	0	3610	C1* *2 Cabin doors	est 9.0	est 2.3	est 2.0	est 40.0	est 1.7*	est 0.7*
Lockheed Model 186	XH-51A XH-51N* *owned by NASA/LRC **one crew only	505** 505**	265** 265**	418 418	76 75	71 71	0 0	>3962 >3962	C1* *2 Cabin doors	est 1.0	est 1.5	est 1.5	est 2.25	est 1.5*	est 0.7*
Lockheed Cheyenne	AH-56A	2210	-	1400	112	107	0	7925	C1	est 1.5 *access is throught 2 canopy doors; one hinged, one sliding, size unavailable	est 1.5	est 1.5	est 3.5	*	*

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TABLE 6-1 (CONTINUED)

Manufacturer's Designations	Other Designations	PAYLOAD (Kg.) Including Fuel	PAYLOAD (Kg.) Excluding Fuel	RANGE (Km.)	SPEED (mps) Max.	SPEED (mps) Cruise	SPEED (mps) Stall	MAXIMUM ALTITUDE (meters)	CABIN OR COMPARTMENT No.	LENGTH (meters)	WIDTH (meters)	HEIGHT (meters)	VOLUME (cu. meters)	DOOR HEIGHT (meters)	DOOR WIDTH (meters)
Sikorsky S-58	CH-34A	2205	-	400	54	43	0	2900	C1	4.14	1.52	1.78	9.91	est 1.22	est 1.36
	UH-34D	2137	-	est 400	54	43	0	est 2900	C1	4.14	1.52	1.78	9.91	1.22	1.36
	SH-34J	1966	-	est 400	54	43	0	est 2900	C1	4.14	1.52	1.78	9.91	1.22	1.36
	S-58B	2259	-	450	55	44	0	2740	C1	4.14	1.52	1.78	9.91	1.22	1.36
	S-58C	2259	-	450	55	44	0	2740	C1	4.14	1.52	1.78	9.91	1.42	0.74
Sikorsky S-61	S-61A	4692	-	1005	73	60	0	4480	C1	7.60	1.98	1.92	28.9	1.68*	0.91*
	S-61B	3738	-	1005	73	60	0	4480						1.52**	1.73**
										*Crew door; **Cabin door					
	S-61L	3122	-	418	66	62	0	3810	C1	9.73	1.98	1.92	36.95	1.68*	0.91*
	S-61N	2896	-	740	66	62	0	3810						1.68**	0.81**
														1.68***	1.27***
										*Crew door; **Cabin door - passenger configuration ***Cabin door - cargo configuration					
									C2	-	-	-	3.54	unk.	unk.
									C3	-	-	-	0.71	unk.	unk.
Sikorsky S-61R	CH-3	3445	-	748	72	63	0	3385	C1	7.89	1.98	1.91	29.73	1.65*	1.22*
	HH-3	3445	-	748	72	63	0	3385						4.29**	1.85**
										*Cabin door; **rear ramp					
Sikorsky S-62	S-62A	1155	-	743	45	41	0	2010	C1	4.27	1.62	1.83	12.45	1.52	1.22
	HH-52A	1188	-	763	48	43	0	3410	C2	-	-	-	1.25	unk.	unk.
Sikorsky S-65A	CH-53A	5875	-	est 413	est 87	est 77	0	est 6000	C1	9.14	2.29	1.98	41.44	*	*
	CH-53D	5677	-	413	87	77	0	6400		*Forward cabin door and rear ramp dimensions unavailable					
	HH-53B	6294	-	869	83	77	0	5610							
	HH-53C	6265	-	869	87	77	0	6220							
SPECIFIC FIXED WING PROPELLER															
Beechcraft Queen Air 70 (NASA/Wallops)		1273	-	max 2663	106	74	35	9145	C1	6.97	1.32	1.45	9.37	1.39	0.69
									C2	-	-	-	0.62	unk.	unk.
Cessna 206 (Meteorology Research Inc.)		767* *one crew only	-	1045	77	58	27	4511	C1	3.48	1.12	1.26	2.80**	1.03**	0.88***
												**payload volume ***2 doors, 1 each side		0.98***	1.08***
									C2	-	-	-	0.34	unk.	unk.

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TABLE 6-1 (CONTINUED)

Manufacturer's Designations	Other Designations	PAYLOAD (Kg.)		RANGE (Km.)	SPEED (mps)			MAXIMUM ALTITUDE (meters)	CABIN OR COMPARTMENT					DOOR	
		Including Fuel	Excluding Fuel		Max.	Cruise	Stall		No.	LENGTH (meters)	WIDTH (meters)	HEIGHT (meters)	VOLUME (Cu. meters)	HEIGHT (meters)	WIDTH (meters)
Cessna 402 (NASA/Ames)		988	-	2338	100	94	35	7980	C1 C2* C3**	4.42 - -	1.42 - -	1.30 - -	6.30 est 2.0 est 0.25	1.21 0.30 0.30	0.58 0.62 0.62
										*Nose baggage compartment has 1 door on each side **Each engine nacelle has a small baggage compartment with one door					
Cessna 411 (Battelle Northwest, Inc.)		1005	-	2090	100	81	38	7925	C1 C2* C3*	4.42 - -	1.42 - -	1.30 - -	6.30 est 2.0 est 0.25	1.21 0.30 0.30	0.58 0.62 0.62
										*C2 - nose baggage, 2 doors; C3 - two engine nacelle compartments					
Douglas B-26 (all data approximate) (NERC/Las Vegas)		-	4500	650	-	130	55	>6000	C1** C2*	6.0 2.75	1.25 1.2(diam.)	1.7 -	12.75 3.11	1.5 unk.	0.7 unk.
										*Nose Compartment **Main cabin has 6 downward looking ports:		Length 0.45 0.38 0.38 0.15 0.13 0.13	Width 0.45 0.38 0.38 0.55 0.13 0.13		
Douglas C-54 (NASA/Wallops 438) (all data approximate)	DC-4	-	4500	est 2500	-	est 70	-	5170	C1	est 15.0	est 3.0	est 2.5	est 110		
Fairchild Hiller M473 (California Air Resources Board)	C-123	6800	-	unavail.	100	76	42	unavail.	unavail.						
Grumman G-134 (NERC/Las Vegas)	OV-1B	997	-	1980	131	91	32	9235	C1* C2 C3 *nose dome	est 0.5 est 0.5 est 0.5	est 1.2 diam est 1.2 diam est 1.2 diam	- - -	est 0.25 est 0.5 est 0.5		
Grumman G-134 (NERC/Las Vegas)	OV-1C	1018	-	2140	135	91	33	9000		same as OV-1B					

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TABLE 6-1 (CONCLUDED)

Manufacturer's Designations	Other Designations	PAYLOAD (kg.) Including Fuel	PAYLOAD (kg.) Excluding Fuel	RANGE (mps) (Km.)	Max.	Cruise	Stall	MAXIMUM ALTITUDE (meters)	CABIN OR COMPARTMENT No.	LENGTH (meters)	WIDTH (meters)	HEIGHT (meters)	VOLUME (Cu. meters)	DOOR HEIGHT (meters)	DOOR WIDTH (meters)
Lockheed NP-3A (NASA/Johnson)	ES-1	19168* *Four crew standard	4318*	unavail.	unavail	unavail.	unavail.	unavail	unavail.						
Lockheed NC-130B (NASA/Johnson)	ES-2	29498* *Four crew standard	9140*	3700	170	150	<50	>7000	C1	12.6 *2 Passenger doors **1 Cargo door	3.13	2.81	121.7	1.83* 2.77**	0.91* 3.05**
SPECIFIC FIXED WING JET															
General Dynamics WB-57F (NASA/Johnson)	ES-3	11981	2138	1120	unavail.	190	unavail.	>12000	C1*	5.34 *Instrument Pallet	2.29	0.71	<8.68	-	-
General Dynamics RB-57 (NASA/LRC)		-	1350	1120	unavail.	190	unavail.	>12000	unavail.						

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specifically noted all information on generic platforms has been taken from Taylor[1]. Information on specific platforms was obtained from NERC/Las Vegas[2] and NASA/LRC[3].

- Payload - Payloads are shown either including or excluding fuel depending on available information. The payload excluding fuel assumes a full standard fuel load is planned. Adjustments in the payload are possible through the addition or deletion of appropriate amounts of fuel. If such is the case adjustments in the range of the platform must be made.

Unless otherwise noted each platform uses 2 crew members totaling 180 kg. This weight is not part of the payload although in some cases these crew members may function as full or part time instrument operators. Additional crew members must be considered as part of the payload.

- Range - All aircraft ranges are shown for operation at cruising speed and at a typical operational altitude. Adjustments for other operating conditions must be made.

- Speed - Aircraft speeds are shown as maximum speed, cruising speed and stall speed under typical conditions. Minimum safe speeds

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[1]Taylor, J. W. R. "Jane's All The World's Aircraft", McGraw-Hill Book Company, New York, N.Y.

[2]NERC/Las Vegas Staff. private communications, October 1973.

[3]NASA/LRC Staff. private communications, October 1973 through January 1974.

are generally considered to be at least 5 meters per second above stall speed. For helicopters the stall speed and minimum safe speed are zero except that there is a speed versus altitude unsafe zone for each type of helicopter. Figure 6-1 shows one typical situation. In the zone below the unsafe area it is assumed that the helicopter has sufficient speed versus altitude to glide to a safe landing in the event of power failure. In the zone above the unsafe area the helicopter has sufficient altitude for autorotation of the rotor to occur and allow a relatively safe rate of descent.

- Altitude - the figure shown in Table 6-1 is the maximum altitude for a typical operation.

- Cabin dimensions - Dimensions and volume of all cabins and compartments are shown. In all cases the main cabin is denoted C1 with other compartments and cargo areas denoted C2, C3, etc. Data for entry doors to the various compartments are shown on the corresponding line. In general cabin data does not include the flight deck. In all cases length refers to the dimension which is approximately parallel to the major axis of the air frame while width is perpendicular to the axis.

6.1.2 Electrical Power

In general all helicopters and fixed wing aircraft have electrical systems which provide 28 volt DC current from generators or alternators driven by the platform engines. If electrical power in excess of standard is required it is possible in some cases to install additional

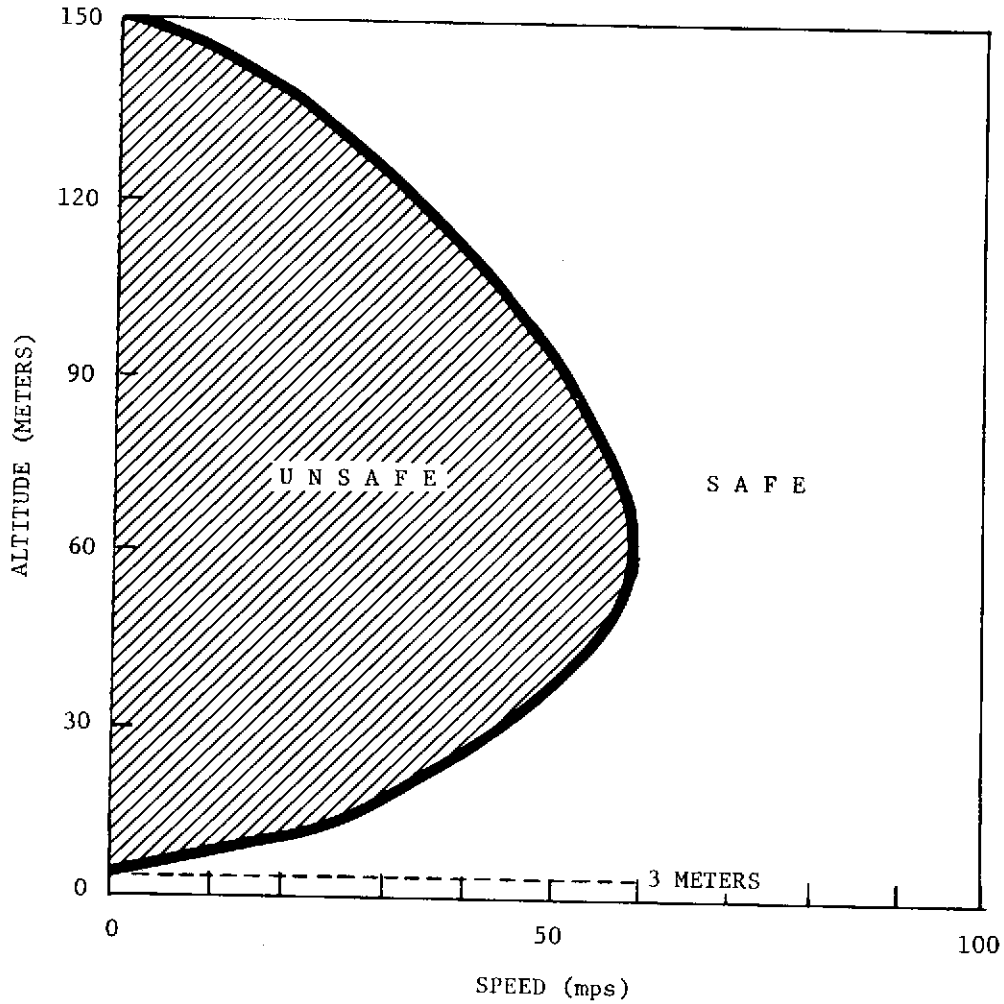

FIGURE 6-1
TYPICAL UNSAFE ZONE FOR HELICOPTERS

generator capacity. However there are practical limits to this procedure for each platform. Some platforms have standard conversion equipment to provide power in other than 28 volt DC especially by conversion to some form of AC. Table 6-2 presents some typical platform electrical information. It must be noted that all of the power indicated in the Table is not available for instrument operation. These figures include the power required to operate the platform. For example it is estimated by Navarro[1] that a maximum of 400 amps of power is used for operation of the NASA/Wallops C-54 type aircrafts. This represents 33% of the 1200 amps available on these aircraft.

6.1.3 Radio and Navigation Equipment

Information pertinent to FAA regulations concerning radio and navigation aids required in the metropolitan Washington area was obtained from Makela[2]. All aircraft, both fixed wing and helicopter, must be equipped with two way radios and transponders for aiding in radar tracking. All other radio and navigation equipment is optional. Due to the operational characteristics of the various remote sensors discussed in Sections 4.0 and 5.0, it is assumed that the platform selected will operate only under visual flight rules (VFR) and most likely in daylight only. Exceptions to this may occur during travel

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[1] Navarro, R., private communication, NASA/Wallops Air Station, January 1974.

[2] Makela, V., private communication, Washington National Airport Control Tower, November, 1973.

TABLE 6-2

ELECTRICAL POWER AVAILABLE ON TYPICAL AIRBORNE PLATFORMS

Airborne Platform	Power Available
Helicopters	
Bell 47	28 volt DC/50 amps
Bell 204	28 volt DC/10 kw
Bell 205, 205A-1	30 volt/300 amps
Bell 212	28 volt DC/400 amps two 2KVA/600 cycle AC (on LARPP helicopters)
Boeing-Vertol 107	two 40KVA/AC one 28 volt DC/200 amps
Boeing-Vertol 114	two 20KVA
Fairchild/Hiller FH-1100	28 volt DC/100 amps
Hughes 300C	28 volt DC/100 amps
Sikorsky S-58	28 volt DC/10 kw
Sikorsky S-61, S-61R	one 28 volt DC/300 amps two 20KVA/115 volt AC
Sikorsky S-62	28 volt DC 26 volt AC 115 volt AC
Fixed Wing	
Beechcraft Queen Air 70	two 28 volt DC/150 amps
Cessna 402	two 28 volt DC/50 amps (100 amp optional)
Douglas B-26	28 volt DC/10 kw
Douglas C-54 (NASA/Wallops)	four 28 volt DC/300 amps two 110 volt 60AC/20 amps
Grumman OV-1C	28 volt DC/>10 kw

to and from the airport from which the platform operates. However in these cases only standard instrument or night flying equipment need be on board. Most of the platforms shown in Table 6-1 are equipped for night and instrument flying.

Standard navigation equipment on board all platforms is generally unsatisfactory for determining platform location to an accuracy acceptable to an urban air quality measurement mission. For example the following accuracies are indicated:

Platform	Equipment	Accuracy (km)
Bell 212 (LARPP)	"Area Nav" Low Frequency LORAN	0.4
Sikorsky S-58	Dual VOR/single DME	0.6
Sikorsky S-58	Dual VOR/double DME	0.2
Bell 204	same as S-58	
Douglas B-26 (NERC)	Doppler radar	0.02
Grumman OV-1B (NERC) OV-1C (NERC)	ARN-30 VOR/TACAN	0.5

Ground based radar tracking either by air traffic control or specialized equipment is much more satisfactory and should be investigated further. In addition consideration should be given to the possible use of a downward looking time lapse camera for assistance in post flight data reduction.

6.1.4 Operational Constraints

Regulations pertaining to aircraft allowable flight time and crew allowable flight time were discussed with Burgin[1]. There are no restrictions on the number of hours of operation of any privately owned platform other than those to comply with CAB air worthiness certification.

Regulations concerning flight crews are contained in FAA regulations Title 14CFR (Civil Flying Regulations) Part 91 (General Aviation). Operators of Air Taxis and Air Carriers are limited to 100 hours per month per crew member. However there are no regulations covering the number of hours a crew member may be on duty at one time. Private aviation has no crew time restrictions.

6.2 Air Traffic Control

Discussions pertinent to air traffic control regulations in the metropolitan Washington area were held with Makela[2]. A summary of these regulations follows.

1. All flights in the Washington area must be coordinated with the Washington National Airport Control Tower.
2. All flights must maintain radio contact and coordination with one of the following as appropriate,
    - Washington National Airport Control Tower
    - Dulles Airport Control Tower
    - Andrews AFB Control Tower

[1]Burgin, R., private communication, FAA National Transportation Safety Board, January 1974.

[2]Makela, W., op. cit.

3. All aircraft must be equipped with transponders and two way radios. Minimum altitude for fixed wing aircraft is 1000 feet above ground or building tops. Flights below 1000 feet are permitted under special circumstances if proper safety conditions are adhered to. There are no altitude restrictions on helicopters other than safety and common sense.
4. There are two prohibited areas,
   - A circle of 2.5 km radius circle centered over George Washington's home at Mt. Vernon, Virginia.
   - The White House prohibited area, bounded approximately by 6th Street East on the East, Rock Creek Parkway on the West, Whitehurst Freeway and K Street on the North and Independence Avenue on the South. Any flights in this area require clearance from the Secret Service. Such clearance is <u>not</u> easily obtained.

6.3 Aircraft Costs

Costs of operating various types of platforms vary markedly depending on whether the platform is commercially leased or obtained from other government agencies on intra/interagency use. The Bell 212 helicopters used in the LARPP project were leased for $20,000 per month plus $200 per flight hour. This cost includes salaries and expenses for one pilot and one mechanic. The leasing company was Petroleum Helicopters, Ltd. Fayetteville, La.

Maintenance on helicopters is always more expensive, required more often and results in longer downtime than for fixed wing aircraft. The Bell 212 helicopter must undergo a mandatory inspection and maintenance after every 100 hours of flight time. This is normally about every 10 to 12 days. This scheduled maintenance takes 3 to 4 days and costs $2,500 per occurrence if done during regular work hours. The cost rises to $5,000 if overtime is authorized. A rough estimate is that maintenance costs for a helicopter are 10 times as great as for a comparable aircraft and the helicopter down time is 4 times as great. A rule of thumb is that 3 helicopters are required to have 2 operational continuously.

A study of the costs of various activities associated with airborne air quality monitoring was made by Wornom[1]. Data was provided for several fixed wing and helicopter platforms which are of interest to this study. Table 6-3 shows this data for four NASA owned platforms, one leased twin engine fixed wing aircraft and one leased helicopter. The platforms are assumed to operating from Langley AFB, Hampton, Va. Costs shown for NASA platforms are intraagency transfers of money from the platform using organization to the platform operating organization.

6.4 Identification of Possible Aircraft

All platforms identified in Section 6.1 were analyzed for possible use for carrying some or all of the payloads described in Section 5.

[1] Wornom, D., private communication, NASA/LRC, November 1973.

TABLE 6-3

COST COMPARISONS FOR SELECTED PLATFORMS

FUNCTION	FIXED WING			HELICOPTOR		
	NASA/Ames Cessna 402	NASA/Wallops Beechcraft Queen Air	Similar Leased Aircraft	NASA/LRC Bell 204	NASA/Wallops Bell 204	Leased Sikorsky S-58
Ferry to LRC	$2560	$100	$300	$0	$1200	$750
Time for Instrument Installation	$0	$0	$120/day	$0	$450/day	$75/day
Flight Operations	$164/hour	$100/hour	$161/hour	$200/hour	$120/hour	$250/hour
Time for Instrument Removal	$0	$0	$120/day	$0	$450/day	$75/day
Ferry to home base	$2560	$100	$300	$0	$1200	$750

All platforms which fulfilled selected criteria which are listed below are shown in Table 6-4. Cost and aircraft availability were not considered in this selection. The principal criteria used were:

1. The net payload of the platform must exceed the weight of the sensor system including operators, after allowance for a normal full fuel load. The gross payloads including fuel were shown in Table 6-1. These must be adjusted for the weight of fuel carried. Typical normal fuel loads are shown in Table 6-5. These capacities vary slightly for the indivudual models in an aircraft series but the values shown are typical.

2. The net volume of space required for sensors and operators must not exceed 50% of the total space shown in Table 6-1. This is to allow room for instrument positioning, access to instruments in flight, space for miscellaneous materials, crew confort, and assumptions in calculating the volume.

3. The average electrical power required must not exceed 60% of the total output of the platform. This is based on an allowance of 33% for platform operation and 7% for instrument surge and spare power.

Examination of the data shown in Table 6-4 shows that each platform listed is capable of supporting system 3, the slightly integrated sensor package. However when the other systems are considered weight is usually the critical factor and eliminates the platform from consideration long before volume and electrical capacity are exceeded. It is possible in many cases to allow for extra sensor weight if only

TABLE 6-4
IDENTIFICATION OF ACCEPTABLE PLATFORMS

AIRCRAFT IDENTIFICATION	AIRCRAFT CAPACITY			SYSTEM I			SYSTEM 2			SYSTEM 3			SYSTEM 4		
	Net Payload Kg	Net Volume m^3	Net Power amps	Weight 1433 Kg % Capacity	Volume 4.26 m^3 % Capacity	Power 95 amps % Capacity	Weight 2685 Kg % Capacity	Volume 8.46 m^3 % Capacity	Power 209 amps % Capacity	Weight 914.9 Kg % Capacity	Volume 1.67 m^3 % Capacity	Power 87 amps % Capacity	Weight 2117.2 Kg % Capacity	Volume 4.76 m^3 % Capacity	Power 198 amps % Capacity
Bell 204 UH-IF	1378	9.95	357	X*	43	27	X	X	59	66	17	24	X	48	55
Bell 204 TH-IF	1378	9.95	357	X	43	27	X	X	59	66	17	24	X	48	55
Bell 205 UH-ID	1239	7.08	300	86	X	32	X	X	X	74	24	29	X	X	66
Bell 205 UH-IH	1223	7.08	300	85	X	32	X	X	X	75	24	29	X	X	66
Bell 205A-1	1196	7.08	300	X	X	32	X	X	X	76	24	29	X	X	66
Bell 212 UH-IN	1006	3.7	400	X	X	24	X	X	52	91	45	22	X	X	50
Boeing-Vertol															
107-II	2463	24.69	3000	58	17	3	X	34	7	37	7	3	86	19	7
CH/UH-46A	2791	24.69	3000	51	17	3	96	34	7	33	7	3	76	19	7
CH/UH-46D	3217	24.69	3000	45	17	3	83	34	7	28	7	3	66	19	7
Basic 107-II	3164	24.69	3000	45	17	3	85	34	7	29	7	3	67	19	7
Boeing-Vertol 114 CH-47C	2631	41.7	1400	54	10	7	X102	20	15	35	4	6	80	11	14
Kaman K-800	1152	40.0	Est 357	X	11	27	X	21	59	79	4	24	X	12	55
Sikorsky S-58															
CH-34A	1313	9.91	357	X	43	27	X	X	59	70	17	24	X	48	55
UH-34D	1245	9.91	357	X	43	27	X	X	59	73	17	24	X	48	55
SH-34J	1074	9.91	357	X	43	27	X	X	59	85	17	24	X	48	55
S-58B	1367	9.91	357	X	43	27	X	X	59	67	17	24	X	48	55
S-58C	1367	9.91	357	X	43	27	X	X	59	67	17	24	X	48	55
Sikorsky															
S-61A	2243	28.9	415	64	15	23	X	29	50	41	6	21	94	16	48
S-61B	1289	28.9	415	X	15	23	X	29	50	71	6	21	X	16	48
S-61L	1926	36.95	415	74	12	23	X	23	50	48	5	21	X	13	48
S-61N	1700	36.95	415	84	12	23	X	23	50	54	5	21	X	13	48
Sikorsky S-61R															
CH-3	1574	29.73	415	91	14	23	X	28	50	58	6	21	X	16	48
HH-3	1574	29.73	415	91	14	23	X	28	50	58	6	21	X	16	48
Sikorsky S-65A															
CH-53A	4062	41.44	Est 415	35	10	23	66	20	50	23	4	21	52	11	48
CH-53D	3864	41.44	Est 415	37	10	23	69	20	50	24	4	21	55	11	48
HH-53B	4481	41.44	Est 415	32	10	23	60	20	50	20	4	21	47	11	48
HH-53C	4452	41.44	Est 415	32	10	23	60	20	50	21	4	21	48	11	48
Douglas B-26	4500	15.86	357	32	27	27	60	53	59	20	11	24	47	30	55
Douglas C-54	4500	110	370	32	4	26	60	8	56	20	2	24	47	4	54
Lockheed NP-3A (ES-1)	4318	>100	>Est 400	33	>4	Est<24	62	<8	Est<52	21	<2	Est<22	49	<5	Est<50
Lockheed NC-130B (ES-2)	9140	121.7	>Est 400	16	4	Est<24	29	7	Est<52	10	1	Est<22	23	4	

X - Does Not Fit Criteria

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TABLE 6-5

NORMAL FUEL CAPACITY FOR SELECTED PLATFORM TYPES

Platform	Fuel Type	Capacity (liters)	Weight (kg)
Helicopters			
ARDC/Brantly	G*	117	92
Bell 47	G	216	166
Bell 206	J*	288	222
Bell 204	J	625	481
Bell 205	J	832	649
Bell 205A-1	J	814	627
Bell 212	J	832	641
Bell 209	J	1345	1036
Boeing Vertol 107	J	1438	1107
Boeing Vertol 114	J	4273	3290
Enstrom T-28	G	114	88
Fairchild Hiller FH-1100	J	261	201
Hughes 300	G	103.5	79
Hughes 300C	G	103.5	79
Hughes 500	J	232	179
Kaman K-800	J	est, 1400	est, 1078
Lockheed XH-51N	J	303	240
Sikorsky S-58	G	1159	892
Sikorsky S-61A&B	J	3180	2449

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TABLE 6-5 (Cont'd)

Platform	Fuel Type	Capacity (liters)	Weight (kg)
Helicopters			
Sikorsky S-61R	J	2430	1871
Sikorsky S-62	J	1516	1167
Sikorsky S-65A	J	2354	1813
Fixed Wing			
Beechcraft Queen Air	G	811	624
Cessna 206	G	246	189
Cessna 402	G	189.25	145
Grumman G-134	J	1125	866
Lockheed NC-130B	J	36636	20358

*G = Conventional gasoline; J = Jet turbine fuel a partial fuel load is carried. The reduction in flight time caused by partial fuel load may not be critical to the experiment since most of the platforms have sufficient fuel capacity for many hours of flight. Each case must be studied on an individual basis. Those platforms which were considered capable of supporting system 2, the heaviest and largest system were:

Boeing Vertol 107, CH/UH-46A

Boeing Vertol 107, CH/UH-46D

Boeing Vertol Basic 107-II

Sikorsky S-65A, CH-53A

Sikorsky S-65A, CH-53D

Sikorsky S-65A, MH-53B

Sikorsky S-65A, MH-53C

Douglas B-26

Douglas C-54

Lockheed NP-3A Electra

Lockheed NC-130B Hercules

It should be reemphasized here that Table 6-4 did not present data on all possible platforms but only selected examples. The results should be interpreted in such a way that other platforms with the same general characteristics as those shown in the table may also be acceptable.

An examination of the capabilities of those specific platforms listed in Section 6.0 was made. Table 6-6 shows which sensor systems can be supported by the various aircraft. Those NASA platforms capable

TABLE 6-6

CAPABILITY OF SPECIFIC PLATFORMS TO SUPPORT
THE FOUR REMOTE SENSOR SYSTEMS

SPECIFIC PLATFORM	SYSTEM 1 Remote Sensors only	SYSTEM 2 Remote Sensors plus LARPP	SYSTEM 3 Integrated Remote Sensors	SYSTEM 4 Integrated Remote Sensors plus LARPP
NERC/Las Vegas				
Bell 212(leased)	-	-	√	-
Bell UH-1H	-	-	√	-
Grumman OV-1B	-	-	-	-
Grumman OV-1C	-	-	-	-
Douglas B-26	√	√	√	√
Cessna C-45	x	x	x	x
Calif. Air Resources Board				
Fairchild Hiller M473	est √	est √	est √	est √
NASA/Wallops				
Bell 204B	-	-	-	-
Douglas C-54(#438)	√	√	√	√
Beechcraft Queen Air	-	-	-	-
NASA/LRC				
Bell 204	-	-	√	-
Sikorsky S-58 (leased)	-	-	√	-
General Dynamics RB-57	-*	-*	-*	-*
NASA/Johnson				
Lockheed NP-3A(ES-1)	√	√	√	√
Lockheed NC-130B(ES-2)	√	√	√	√
General Dynamics WB-57F (ES-3)	-*	-*	-*	-*
NASA/Ames				
Cessna 402	-	-	-	-
Meteorology Research Inc.				
Cessna 206	-	-	-	-
Battelle NW, Inc.				
Cessna 411	est -	est -	est -	est -

SYMBOLS:
- \- Platform not suited for system shown
- √ Platform acceptable for system shown
- x Sufficient data not available for judgement
- -* Eliminated due to crew requirements and poor performance at low altitude

of supporting all systems are:

NASA/Wallops	Douglas C-54
NASA/Johnson	Lockheed ES-1
NASA/Johnson	Lockheed ES-2

In addition the NASA/LRC Bell 204 will support the slightly integrated remote sensor system.

6.5 Payload Installation

Due to the current stage of development of most of the instruments and the fact that each of the possible platforms is a unique entity it is not possible at this time to discuss the detailed installation requirements for one instrument system and one specific platform. Therefore this section will discuss general installation comments. The instrument packages under consideration are those discussed in Section 5, Payload Descriptions.

6.5.1 Instrument Considerations

As noted earlier, the best allocation of space in the platform will require careful planning which takes into account the unique characteristics of each instrument and its support equipment. Listed below are some of the general installation requirements of each instrument,

HSI - down looking, access required, 120 VAC

LACATE - side looking

MAPS - down looking, access required

CIMATS - down looking, access required

LIDAR - down looking using a deflection mirror

Grab Sampler — input plumbing as short as possible
LARPP Sensors — most instruments require 120 VAC.

Based on these features and the amounts of available space, the instruments should be deployed on the platform with significant attention paid to the ability of the operator to have access to those parts of the instrument which may require inflight attention.

6.5.2 Operator Considerations

Significant consideration must be given to convenience of movement and safety of the flight crew and instrument operators. In addition to support requirements discussed in Section 7 each instrument operator should have access to the following

Clock

Navigation Information

altitude

airspeed

heading

attitude

General Instrumentation

oscilloscope

voltmeter

power source and circuit breakers

control panel for remotely controlled instruments

intercom to all other crew members

View of Ground Directly Beneath Platform

direct and/or closed circuit TV

Safety consideration should be a primary factor in the distribution of instrumentation. Motors, pumps and gear assemblies should be well covered. Walkways and seating areas should be clear of clutter and wires. Cryogenics, film and magnetic tapes should be safely stored. A minimum number of workers is advantageous from the points of view of safety, convenience and load.

6.5.3 Recommendations

Installation of complicated instruments on platforms can be somewhat simplified by having the many instruments share support equipment and operators as was done for the slightly integrated systems discussed in Section 5. In addition, fully automatic or remotely controlled instruments allow several simplifications. The instruments can be stored in safe areas out of the crew area of the craft, can be installed and removed with more ease and have more access to openings in the fuselage. Remote control also solves special problems, such as the requirements of the LARPP/Grab Sampler. These devices require sampling tubes which are as short as possible to reduce the lag time. By operating these packages in remote control they can be placed in the nose or in a forward area where direct access to high speed flow, uncontaminated by the platform can be found.

The actual allocation of space to instruments and operators would, of course, be based on the final choice of an instrument package and aircraft. The number of detailed decisions involved in that process preclude any more than the general discussion which has appeared here.

7.0 SUPPORT REQUIREMENTS

7.1 Auxiliary Data for Sensors

The various experiments to be flown require supporting data to assist in data reduction and interpretation. Table 7-1 shows the auxiliary data required by the various experiments for data reduction. In addition interpretation of the results would be greatly facilitated by acquisition of all available air quality data from the local agencies plus selected meteorological data. It is recommended that the following data be obtained from standard sources during all flight periods over Washington, D.C.

- All continuous air quality data measured.
- Hourly surface weather observations and all special observations from Washington National Airport, Dulles Airport, Andrews AFB and Baltimore-Washington International Airport.
- The 1200Z and 0000Z rawinsondes from Dulles Airport (Sterling, Va.) during the flight period. Additional rawinsonde launches should be requested.

It is further recommended that a ground air quality monitoring station be established at the site of the rawinsonde facility in Sterling, Va. This station is intended for measuring background air quality and for airborne calibration of the remote sensors. This facility should be equipped with a sensor system similar to that of the LARPP airborne system. Similar stations may be desired at additional locations.

7.2 Ground Support for Sensors

The various sensors will require ground support which will include,

TABLE 7-1

AUXILIARY DATA REQUIRED FOR DATA REDUCTION

	Temperature Profile	Humidity Profile	Ground Temperature	Pressure Profile	Column Density
HSI	√	√			
LACATE	√ ($\pm 2^{\circ}K$)		√		
COPE					√ (CO_2)
CIMATS					√ (CO_2)
LIDAR	√			√	
MAPS	√ ($\pm 2^{\circ}K$)	√	√		

- Sources of cryogenic materials,
  1. Liquid nitrogen
  2. Dry ice
  3. Glycol
  4. Liquid helium
- Laboratory for Grab Samples - Rapid access to an analysis laboratory is essential to the success of any grab sample experiment.
- Data Gathering and Reduction Support - For a flight program of any reasonable span a sufficient quantity of magnetic data tapes must be available at the base of operation. In addition a computer facility must be available for rapid reduction of data for any operational system.

7.3 Platform Support

Support for the platform will generally be available from standard sources. In addition to standard logistics and maintenance the platform will require,

- Weather forecasts and current weather from FAA sources during all flight planning and operation.
- Air traffic control advisories as needed.
- Navigational aid either by air traffic control radar tracking or provision of a temporary special radar tracking facility.

8.0 RECONNAISSANCE SYSTEM ANALYSIS

Conclusions can be drawn from the results of Sections 2, 3, and 4 with respect to the required instrument performance and optimum flight patterns over Washington, D.C. for a given set of meteorological data. Output from the models provides suggestions as to the range of pollution values expected for both SO_2 and CO. Further use of model data provides input to a statistical method for selecting the most appropriate flight plans within the modeled area.

A technique is also formulated for analyzing the response of the various remote sensing instruments to pollution distributed on two spatial scales. The scales are those defined by the resolution of the dispersion models (~75 meters) and the scale on which actual pollution is distributed (~7.5 meters or less). Fluctuations in the pollution level as a function of averaging time is also discussed as is the influence of the instrument limitations on interpretation of the data.

8.1 Determination of Flight Pattern

Critical pollution levels were established for the CO predicted values and for the SO_2 predicted values. The frequency of predicted values exceeding these levels was used as the basis for a linear regression. The lines defined by this analysis describe potential straight line flight patterns covering the areas which most frequently experience significant CO and SO_2 levels. A more detailed discussion of this technique and its limitations appears in the following sections. As an example, the technique is applied to data from 10 hours of July 18, 1972.

8.1.1 Philosophy of Approach

The objective of this section is to establish a viable technique for determining flight patterns which will, with reasonable reliability, pass through regions of high pollution as predicted by air quality dispersion models using a variety of meteorological and emissions data. Further, it is intended that this example present a technique which can be exercised for any set of hours and/or days. Ideally, the flight plan analysis could be performed for various sets of meteorological conditions, prior to their occurrence. Then, whenever a flight was scheduled, the pilot of the airborne remote sensing system could obtain a predetermined flight plan for the meteorological conditions occurring at the time of his scheduled flight.

8.1.2 Analysis Technique

Straight flight paths with the fewest number of linking turns are most desirable because the sensors cannot be operated when the aircraft is banked. However, a single straight path over the city will not be able to provide sufficient detail of the spatial distribution of the pollution for the area of interest. Consequently, it is suggested that the entire area to be studied be divided into subareas and a separate flight pattern computed for each subarea. The number of subareas used will be dependent on the size of the total area being studied and the degree of resolution desired. A minimum number of subareas, based on the above criterion, is desirable in order to minimize the number of turns required to link the flight paths. For this example, based on Washington, D.C. and its surrounding area, four subareas were chosen.

In choosing pollutant critical levels to be used for defining areas of special interest, two main facts must be considered - the ambient air quality standards and the highest values recorded in the area. The national primary standard for carbon monoxide is 10 mg/m^3 (9 ppm) for an 8-hour period, and the national primary standard for sulfur dioxide is 365 $\mu g/m^3$ (0.14 ppm) for a 24-hour period. Based on these standards and concentrations predicted by the models, the critical levels chosen for this example were 1 ppm for CO and 100 $\mu g/m^3$ for SO_2.

Next, maps showing the distribution of CO and SO_2 values are reviewed for each hour to be considered. The occurrence of a CO value exceeding the CO critical level was weighted the same as the occurrence of an SO_2 value exceeding the SO_2 critical level. For convenience in this data analysis, MITRE considered values at one kilometer intervals, although significant increases in the amount of data used for the analysis could be obtained by using a shorter interval. The number of times that each of these points exceeds the critical levels defined earlier is recorded on another map. A typical result of this type of analysis is shown in Figure 8-1 for one of the Washington subareas (the NE quarter).

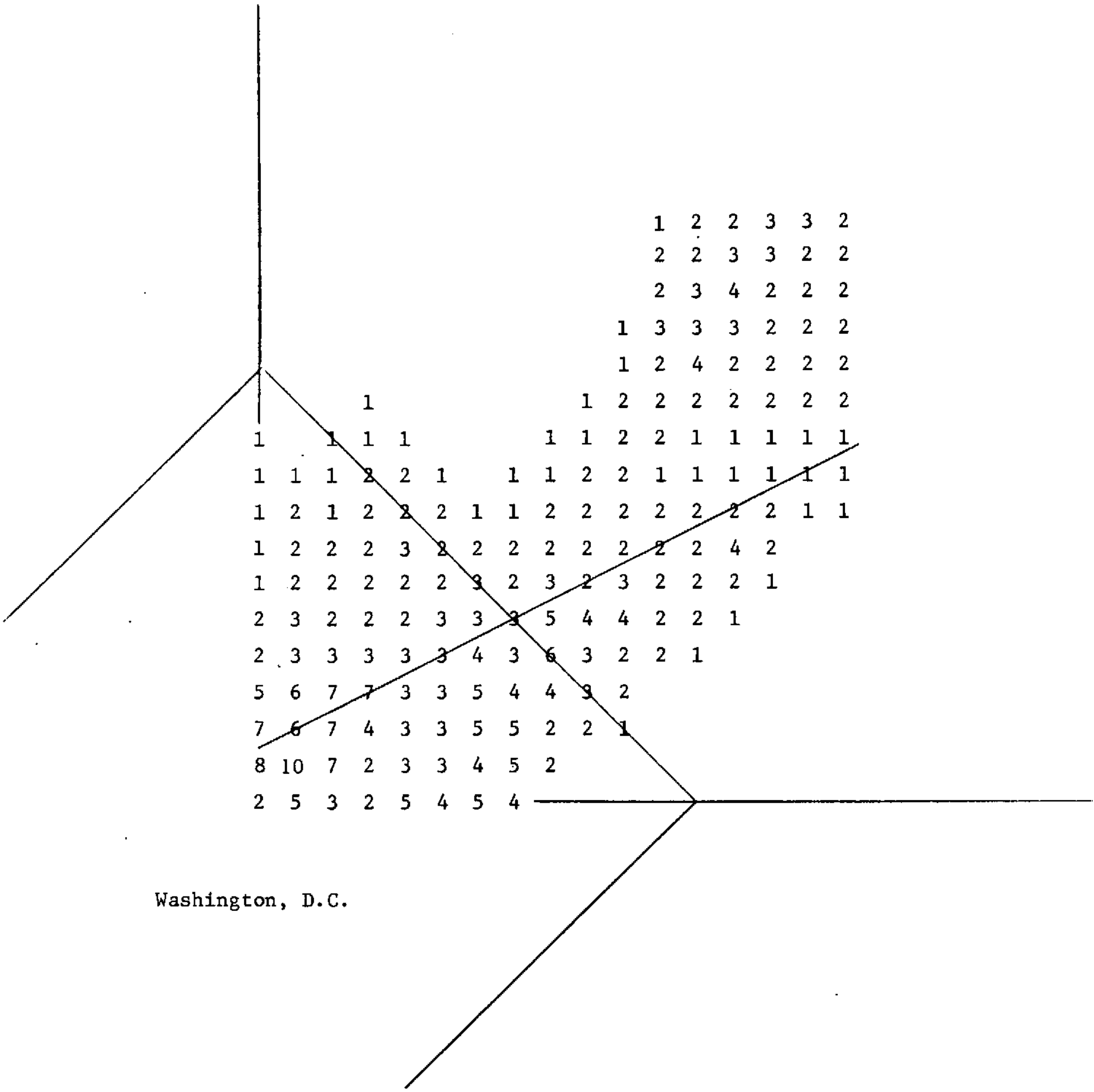

FIGURE 8-1
OCCURRENCES OF POLLUTION IN EXCESS OF THRESHOLDS
OF SO_2 AND CO

Since the relative abundance of pollution occurrences at each point is considered a criterion for flying over that point in the city[1], a statistical method such as linear regression analysis can be used to define the straight line which most closely reflects the pollution distribution. Such an analysis was applied to each subarea of the example.

The results of the analysis were in the form of the slope and intercept of the trajectory most effective at coming close to the pollution. The range of slopes allowed within the indicated confidence level is also given along with the predicted correlation coefficient.

8.1.3 Presentation of Results and Conclusions

Results of the regression analysis are shown in both Figure 8-2 and Table 8-1, which follow. Each trajectory indicates, within the indicated confidence level, the path which minimizes the mean square error. With exception of the restricted zone near the Capitol, White House, and National monuments, the predicted flight plans link up fairly well at the intersections allowing a minimum in flight corrections. Restrictions in flight paths have been discussed in Section 6.2.

The statistical analysis indicates high correlations in the Northwest and Northeast regions and appropriately, a small range in the slope

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[1] This distribution of pollution events is also useful in the allocation of ground stations. Given the number of stations determined by the analysis of Section 9, the optimum allocation would rely on the probability that a site exceed the threshold. The site with the highest probability would receive the first station, the next highest the second station and so on.

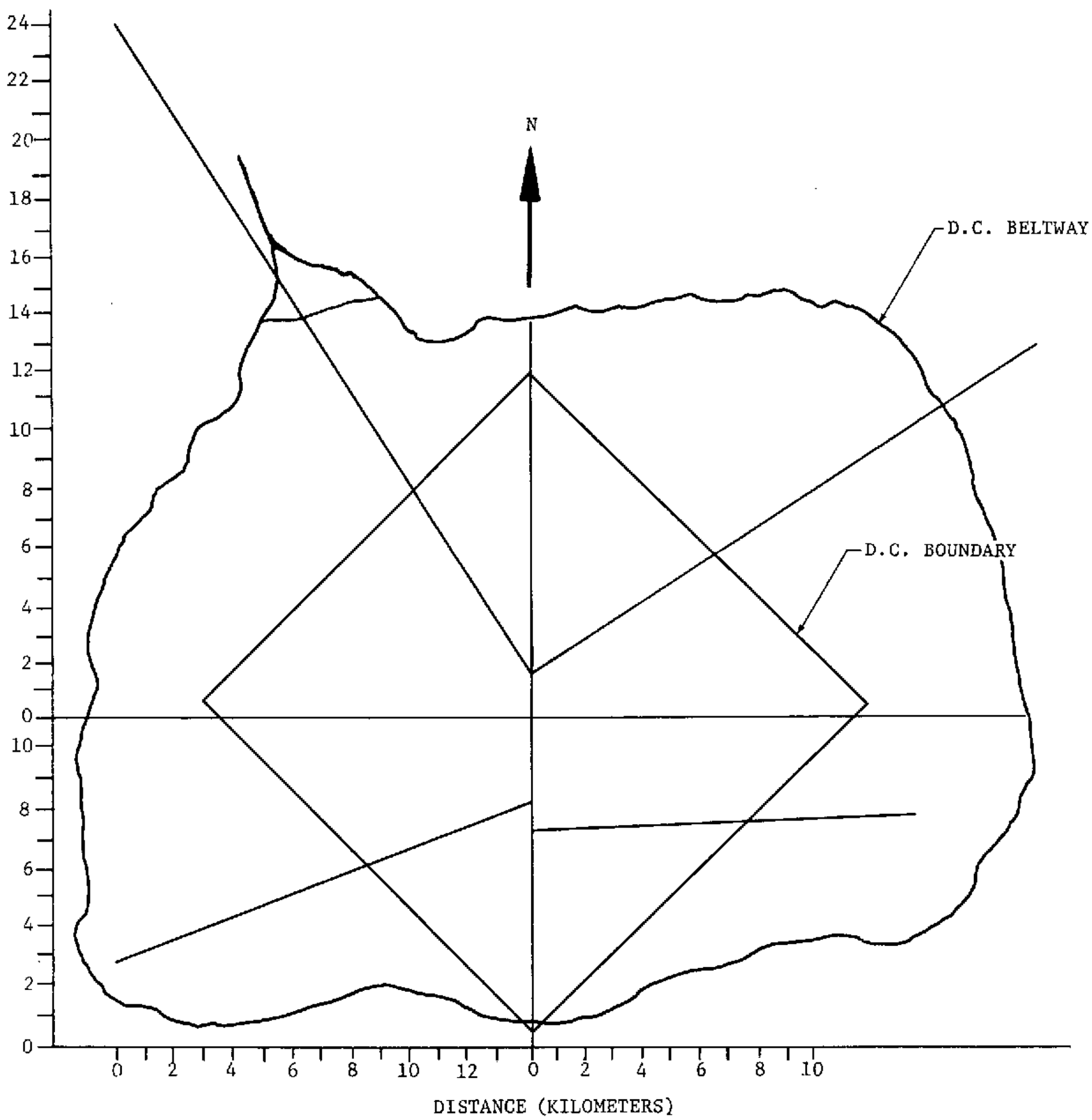

FIGURE 8-2
PROPOSED FLIGHT PATTERNS, JULY 18, 1972

TABLE 8-1

RESULTS OF THE REGRESSION ANALYSIS
USED TO DETERMINE OPTIMUM FLIGHT PATHS

STATISTICAL PARAMETER	QUAD 1 SW	QUAD 2 SE	QUAD 3 NW	QUAD 4 NE
Slope	0.373	0.037	-1.595	0.642
Y-Intercept	2.642	7.069	23.693	1.590
Number of Points	82	117	121	466
Correlation	0.350	0.049	-0.626	0.677
Upper Bound of Slope*	0.596	0.179	-1.231	0.706
Lower Bound of Slope*	0.15	-0.105	-1.960	0.577

*Based on 95% confidence level.

necessary to give 95% confidence levels. The Southern quadrants have lower correlations and larger ranges for the predicted slope.

For the hours considered, SO_2 dominates in the Eastern quadrants due to predominant winds in that direction. CO emissions are very much associated with roads and intersections and therefore appear in all areas.

The upper and lower bounds on the slope are determined by the t test.[1] A value of t is chosen which generates a range of slopes which provide that for a given level of confidence (95%) the true mean slope lies within that range. The true mean is defined as the mean derived from an infinite set of data with the same statistical distribution as the set in question.

Automatic generation of charts of this type could be made by generating the pollution distribution tables for each hour or day of interest. Normally these data are taken out of the computer and converted to a map showing the distribution of pollutants. In lieu of this, information produced by the models would be accumulated for the various runs. The critical levels could then be defined and entered into the computer. Pollution events would then be analyzed statistically and the appropriate trajectories produced. This technique could produce short turnaround between the input of data and the useable result.

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[1] Brownlee, K.A. Statistical Theory and Methodology in Science and Engineering, J. Wiley & Sons, N.Y., 1965, Page 560.

8.1.4 Limitations

The establishment of trajectories based on statistical methods is subject to qualifications. Arbitrary choices must be made of the critical pollution level, the hours and days sampled, the statistical confidence level required and others.

For simplicity in calculation and in anticipation of problems in navigation, straight line paths in the quadrants were chosen. A limitation of this technique is that it does not include the advantages of planning flight paths which cross directly over the sites of ground stations. This could help with respect to correlation of ground and airborne data although instrument limitations will tend to prevent exact comparison.

A fundamental consideration is that of the number of regions into which the city is segmented for the statistical determination of the flight plan. As noted in Section 8.1.2 the city has been divided into quarters, each containing a flight path 5-10 km in length. This tends to introduce some errors since the body of data available for the trajectory determination is by definition only about one-fourth of the total number of points.

In a more advanced version of this technique, each model could be run at its highest resolution (~100m), which would provide a factor of 100 increase in the number of data points. In this way the correlation of the regression could be improved. In addition, shorter paths in smaller areas could be considered since sufficient data points would be available for the analysis.

For simplicity in dealing with the first example of such a calculation, equal weight has been given to events of excess CO or SO_2, without regard to the relative occurrence of such events or their potential health hazard. Interpretation of the data to include the relative health and damage hazard would require specific knowledge of the danger of a particular level of pollution after a specified exposure time. Detailed knowledge of this type is not available so that equal danger has been supposed.

The absolute accuracy of the model is also a factor in the general limitations of this technique. The output of the model must be compared with a threshold level. Gross inaccuracies in the output would tend to change both the rate of occurrence and location of excess levels of pollutant, thereby distorting the statistics. Model limitations are discussed in Section 2.8, although it is difficult to quantify the influence of these considerations with respect to the output of the statistical analysis.

8.2 Remote Sensor Performance Versus Air Pollution Dispersion Model Results and Measured Microscale Pollution Variations

The evaluation of various sensors can be made on various scales - time, space and level of pollution. This evaluation can most conveniently be done by using data provided by one of the dispersion models. However, consideration must be given to the relative spatial and temporal resolution of the model, the instrument and typical ground stations. The ability of the sensor to resolve the measured variations in pollution is of primary interest. The dispersion models have resolutions of hundreds of meters and represent essentially an average pollution distribution for that 100 x 100 meter region over one hour. The remote sensors may be constructed to resolve to less than 100 meters and on the order of seconds in time. These variations may be compared to the spatial distribution, level of pollution and time variations observed at ground stations. Experience at the Washington, D.C. CAMP station indicates that concentration changes of 2 orders of magnitude can occur over distances as short as 15 meters when measuring CO. Further, Larsen[1] has shown that averaging time of the measurement system strongly influences the range of values observed: measurements of the average pollution over a year's time vary little from year to year while subsequent measurements of the average pollution during subsequent 1 second intervals may vary 5 orders of magnitude.

As noted by Dr. Ron Greenwood of NASA, the disparity between ground sensors, remote sensors and the models with respect to their temporal and spatial resolution should be investigated. This has motivated a consideration of the problem on the two spatial scales of 75 meters (the approximate model resolution), and 7.5 meters (the approximate distance over which the pollution varies.) The amplitude variations over small distances can be somewhat ignored in the analysis since it is approached from the point of view of relative response. Thus, comparisons have been made for several sets of instrument parameters to pollution distribution in these ranges of spatial and level of pollution variations.

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[1] Larsen, R. I., "A Mathematical Model for Relating Air Quality Measurements to Air Quality Standards", U.S. EPA, Office of Air Programs Publication No. AP-89, U.S. Government Printing Office, Washington, Nov. 1971.

8.2.1 Analysis Technique

Any review of the capability of remote sensing instrumentations must necessarily include an analysis of the instrument resolution. In this application the computation of the instrument performance characteristics will be used to evaluate the effectiveness of the instrument at detecting variations in pollution levels as predicted by computer models (see Section 2.7). As an example, an instrument of the GFCI type mounted in a C-54 is considered. This combination has a speed of 75 mps, a field of view of 0.13 radians and a time constant which may range from 0.01 to 10.0 seconds.

In an evaluation of any electronic instrument which has a non-zero time constant, the convolution is used.[2] That is, if the instrument has a response function, h(t), and a signal g(t) is being propagated through the device, the output is given as:

$$f(t) = \int h(t-t') \, g(t') \, dt' \qquad 8.1$$

where the limits are established by the problem at hand. Many of the remote sensing instruments of interest here have exponential response functions

$$h(t) = \frac{1}{\tau} \, e^{-t/\tau} \qquad 8.2$$

If g(t) is a unit step, starting at t = 0

$$f(t) = \frac{1}{\tau} \int_0^t e^{-(t-t')/\tau} \, dt'$$

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[2] Frederick, Dean K. and A. Bruce Carlson, Linear Systems in Communication and Control, J. Wiley & Sons, N.Y., 1971, Page 94.

$$= 1 - e^{-t/\tau}$$

which is the expected result.

Now consider another factor which limits the resolution of remote sensors; that is, the field of view. Each region within the field of view, assumed to be rectangular, responds to input functions as shown in equation 8.1. The total response of the instrument at any time is then an accumulation of the responses at that time by the elements in the field of view. Thus, the response will be

$$f(t) = \frac{1}{\tau} \int_x \int_t e^{-\left(\frac{t-t'}{\tau}\right)} g(x)\, dt'dx \qquad 8.3$$

where x ranges over the dimensions of the field of view, D, in the direction of travel of the platform. If

$$g(x) = 0 \text{ for } vt < 0$$

x ranges from vt-D to vt for vt>D and from 0 to vt for vt<D since in the second case part of the field of view is not yet receiving data. As an example calculation, a rectangular step beginning at t=0 produces, for vt<D an output of

$$f(t) = \frac{1}{\tau D} \int_o^{vt} \int_o^{t} e^{-\left(\frac{t-t'}{\tau}\right)} dt'dx = \frac{vt}{D} - \frac{v\tau}{D} (1-e^{-t/\tau}) \quad .$$

If vt>D

$$f(t) = \frac{1}{\tau D} \int_{vt-D}^{vt} \int_{o}^{t} e^{-\left(\frac{t-t'}{\tau}\right)} dt'dx$$

$$= 1 - e^{-t/\tau} \frac{v\tau}{D} (e^{D/v\tau} - 1)$$

which is the result quoted in Section 4.2.3.

8.2.2 Application of the Technique

We may now proceed to utilize Equation 8.3 for a specific application in the instrument evaluation. The models discussed in Section 2 have resolutions of approximately 75 meters due to lack of knowledge of the micro-meteorology, lack of detail in emissions data, approximations in the computer program, etc.

Using that value as guide for the best resolution available from the model the intention is to determine the ability of remote sensors to follow the results produced by the model. It is further acknowledged that the true spatial distribution of pollutants may be based on smaller scale (10 meters or less) so that each set of instrument parameters should be tested for resolution against pollution concentrations distributed on that scale.

In either case the pollution distribution can be conveniently described as

$$g(x) = A \sin^2 \frac{\pi}{R} x$$

where R is the wavelength of the spatial oscillation variations and A is the maximum pollution level. As previously mentioned A may vary locally by up to 5 orders of magnitude. Instrument performance is therefore discussed in relative terms (A is defined to be 1). Then the instrument response is defined by

$$f(t) = \frac{1}{\tau D} \int_x \int_t e^{-\left(\frac{t-t'}{\tau}\right)} \sin^2 \frac{\pi}{R} x \; dt' dx$$

$$= \frac{1}{\tau D} \int_t \sin^2 \frac{\pi}{R} x \; (1 - e^{-\frac{x}{v\tau}}) dx \qquad 8.4$$

The integration must be performed for the two cases

$vt<D$ and $vt>D$

For $vt<D$

$$f(t) = \frac{1}{\tau D} \int_0^{vt} \sin^2 \frac{\pi}{R} x \; (1 - e^{-\frac{x}{v\tau}}) \; dx \qquad 8.5$$

For $vt>D$

$$f(t) = \frac{1}{\tau D} \int_{vt-D}^{vt} \sin^2 \frac{\pi x}{R} \; (1 - e^{-\frac{x}{v\tau}}) \; dx \qquad 8.6$$

The results of these calculations have been plotted in the following two Figures (8-3 and 8-4) for an expected set of instrument parameters.

Remembering that D and τ are the field of view and time constant, respectively, the influence of these factors on instrument performance can be seen. Both figures illustrate the amplitude and peak position errors which occur. The amplitude errors are evident in the figures

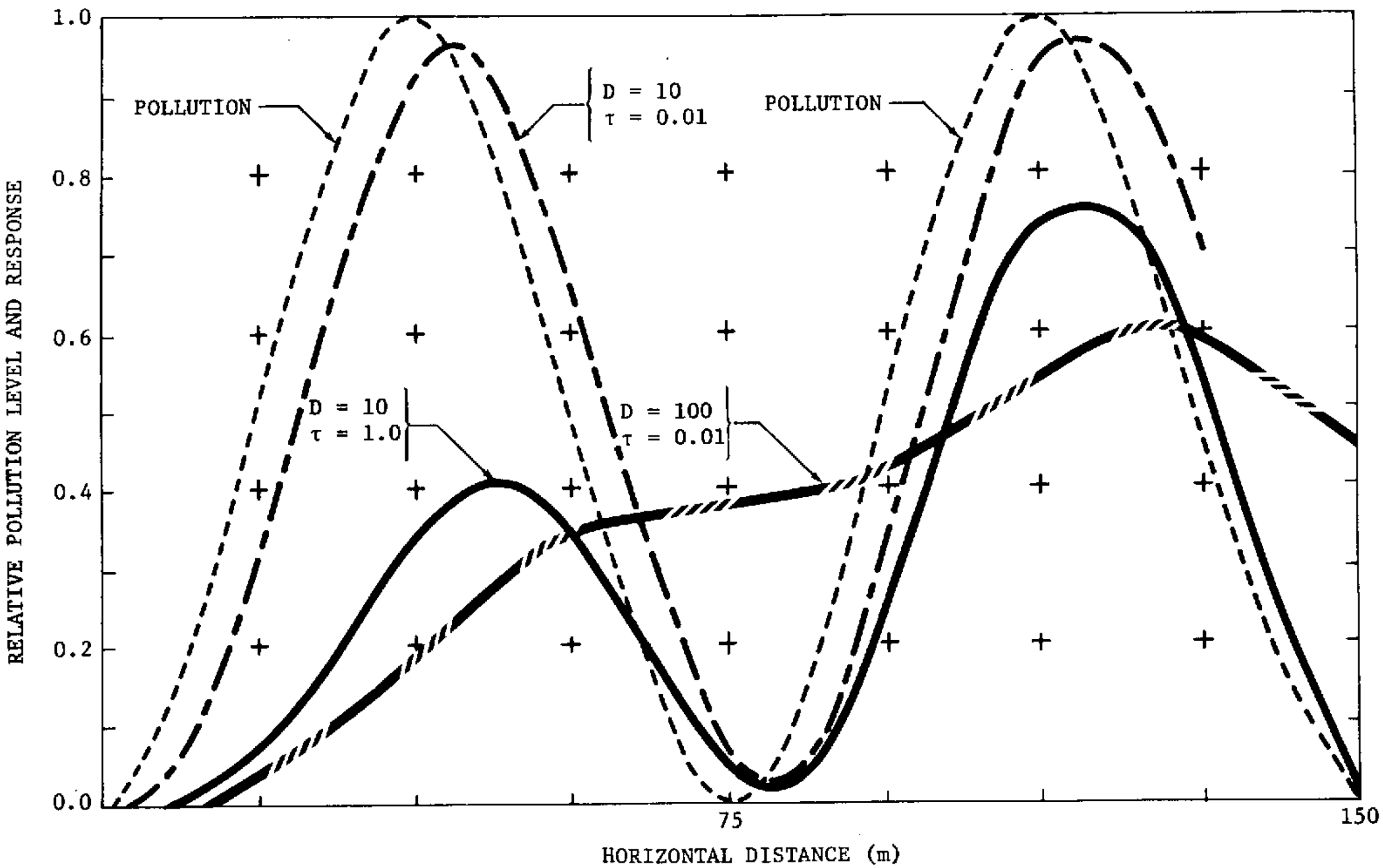

FIGURE 8-3
RESPONSE OF AN INSTRUMENT WITH THE INDICATED PARAMETERS
IN ALL CASES R = 75 m AND V = 75 mps

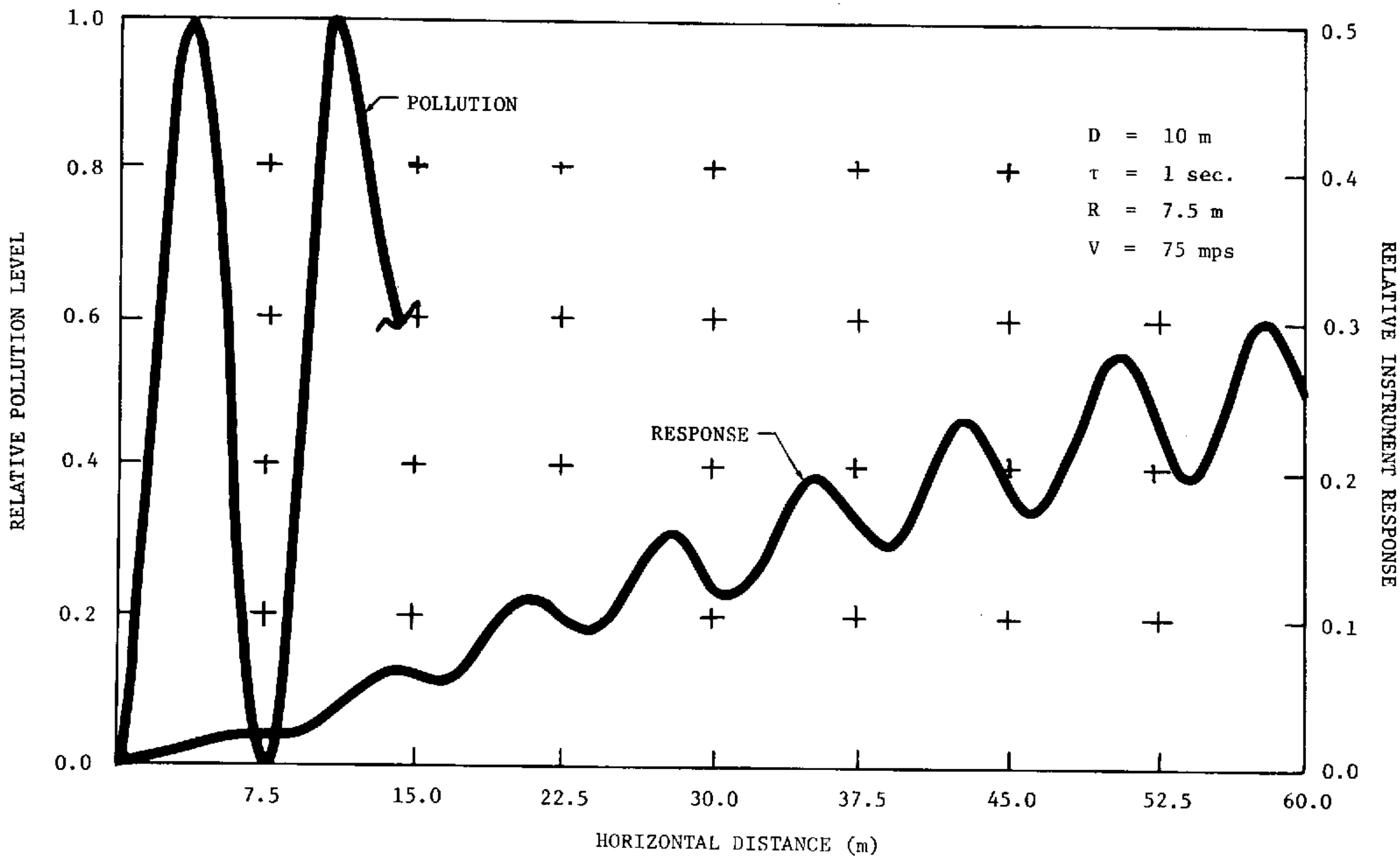

FIGURE 8-4
RESPONSE OF AN INSTRUMENT WITH THE INDICATED PARAMETERS

TABLE 8-2

RESPONSE OF INSTRUMENT WITH CHARACTERISTICS SHOWN.
(INDICATED ARE THE AMPLITUDE AND TIME ERRORS AFTER THE FIRST CYCLE OF POLLUTION)

FIRST PULSE

R=75m, V=75mps, D=10m (first peak at 0.5s)

τ	Amp.	Peak time (sec)	ΔA	Δt (sec)
0.01	0.985	0.565	0.015	0.065
0.1	0.978	0.570	0.022	0.070
1.0	0.407	0.630	0.593	0.130
10.0	0.052	0.650	0.948	0.150

R=75, V=75, D=10 (first peak at 0.5s)

τ	Amp.	Peak time (sec)	ΔA	Δt (sec)
0.01	0.603	1.665	0.397	1.165
0.1	0.601	1.670	0.399	1.170
1.0	0.374	1.775	0.626	1.275
10.0	0.062	1.820	0.938	1.320

R=7.5, V=75, D=10 (first peak at 0.05s)

τ	Amp.	Peak time (sec)	ΔA	Δt (sec)
0.01	0.601	0.167	0.399	0.117
0.1	0.374	0.178	0.626	0.128
1.0	0.062	0.182	0.938	0.132
10.0	0.007	0.183	0.993	0.133

R=7.5, V=75, D=100 (first peak at 0.05s)

τ	Amp.	Peak time (sec)	ΔA	Δt (sec)
0.01	0.510	1.365	0.490	1.315
0.1	0.482	1.380	0.518	1.330
1.0	0.241	1.390	0.759	1.340
10.0	0.035	1.395	0.965	1.345

TABLE 8-3

INDICATED AMPLITUDE AND TIME
ERRORS AFTER 10 CYCLES OF POLLUTION

τ	Amp.	Peak time (sec)	ΔA	Δt (sec)
		R=75m, V=75mps, D=10m (10th peak at 10.5s)		
0.01	0.985	10.565	0.015	0.065
.1	0.985	10.565	0.015	0.065
1.0	0.985	10.565	0.015	0.065
10.0	0.641	10.570	0.359	0.070
		R=75, V=75, D=100 (10th peak at 10.5s)		
0.01	0.603	10.665	0.397	0.165
0.1	0.603	10.665	0.397	0.165
1.0	0.603	10.665	0.397	0.165
10.0	0.381	10.675	0.619	0.175
		R=7.5, V=75, D=10 (10th peak at 1.05s)		
0.01	0.603	1.067	0.397	0.017
0.1	0.603	1.067	0.397	0.017
1.0	0.381	1.068	0.619	0.018
10.0	0.057	1.069	0.943	0.019
		R=7.5, V=75, D=100 (10th peak at 1.05s)		
0.01	0.510	1.367	0.490	0.317
0.1	0.482	1.380	0.518	0.330
1.0	0.252	1.392	0.759	0.342
10.0	0.035	1.394	0.965	0.344

since in no case do the instrument responses reach the value 1.0. The peak position error refers to the displacement of the peaks produced by the instrument relative to the peak in the pollution distribution. This can also be referred to as a time error since the time error times the aircraft velocity equals the position error. In general, the peak position error will be an increasing function of both D and τ accompanied by an increased distortion in the shape of the response curve, as noted in Figure 8-3 for D = 100, τ = 0.01. Figure 8-4 illustrates a case where the spatial distribution is smaller than the field of view or the product of the time constant and the aircraft velocity. Those conditions are not met simultaneously for any of the sets of parameters in Figure 8-3. The result is that, in Figure 8-4, two general trends can be seen. They are a gradual increase of the average value of the response (eventually reaching a value of 0.5) and a gradual increase in the response to each pollution cycle. This last feature is also accompanied by a nearly constant peak position error of approximately 3 meters. Performance of this kind can hardly be considered adequate to resolve actual pollution variations which have random amplitude and spatial variations which would make inference of the actual pollution impossible. Further, two Tables (8-2 and 8-3) have been prepared which indicate the relative response of an instrument under various conditions. This has been done for the response after one cycle of the ground pollution and after 10 cycles.

The tables specify the numerical increases in amplitude and time error as a result of increases in the time constant τ or the field of view, D. It should be noted that on the 75 meter scale, the smallest time error is 0.065 seconds which still produces, when multiplied times the aircraft velocity of 75 meters per second, a spatial error of over 8.5 meters. In general this is a tolerable error but if correlation between the airborne and ground stations is desirable, this position error problem must be considered. In virtually every case, the instruments operating with 10 second time constants produce unacceptable errors in amplitude and time.

The amplitude errors noted in the tables and figures are less troublesome since the remotely sensed data can be multiplied by an appropriate correction factor if the instrument properties and general characteristics of the pollution distribution are known. The correction of temporal, thus position errors, is more complex and would require detailed post-flight data analysis.

8.2.3 Other Sensor Evaluations

Resolution is only one of several parameters which must be investigated for complete sensor evaluation. The dynamic range is of some importance. The results of Section 4 indicate that each of the instruments will have adequate dynamic range with upper and lower limits of operation appropriate to measure the expected pollution levels as indicated by an inspection of the output of the models for SO_2 and CO. Typical ranges and average values are shown for two days selected at random.

TABLE 8-4

EXTREMES OF MODELED AND MEASURED CO AND SO_2 POLLUTION LEVELS

		CO (ppm)	SO_2 (g/m^3)
Modeled	Upper	3.78	953.3
	Lower	0.4	0.6
Measured[1]	Upper	50	1050
	Lower	0.5	25

8.2.4 Conclusions

Several examples of instrument response have been worked for pollution distributions having scales of 75 and 7.5 meters. The goal was to demonstrate a technique for solving such problems and to generate several example results. This technique quantifies the errors resulting from limited instrument performance analysis. A more complete analysis will be necessary for comparison of ground-based and aircraft sensors when high quality ground-based sensor data become available.

[1] Federal Register, Vol. 36, No. 228 - Thursday, November 25, 1971.

9.0 SYSTEMS COSTS COMPARISON

Thus far no detailed program description has been developed for the type of airborne remote sensing system being envisioned in this study. More instruments, platforms and models will be investigated before initial designs of possible systems are developed. When the design phase is begun for such an airborne remote sensing system, it may also be necessary to carry out a detailed cost/benefit analysis. This analysis would compare various designs of the airborne remote sensing system with each other, and compare these systems to other data acquisition systems, such as a ground network.

Some fundamental questions, such as what pollutants should be measured and what should the resulting data be used for, still must be answered in order to define the exact nature of the airborne remote sensing system being envisioned. Until these questions are resolved, neither the project description nor the cost/benefit analysis will have any value. Nevertheless, it is not too early to begin considering economic factors related to such a project and the economic feasibility of such a remote sensing system.

Three alternative systems have been chosen for an initial cost comparison. They are an enlarged system of ground stations, an enlarged system of ground stations operated in combination with the execution of air quality dispersion models, and an aircraft air quality monitoring system. Cost factors related to the acquisition of each of these systems are discussed in the sections which follow. As a more detailed project description begins to develop for the remote sensing system, it will be possible to make some estimates of the operating costs of this system and to compare these to the operating costs of alternative systems.

The major problem, which hampers cost comparisons of both the acquisition and operating costs for the three types of systems used in this study, is that the systems do not yield precisely comparable data. It is not probable that system designs can be altered sufficiently to completely eliminate this problem. Consequently, to compare the systems, a value must be attached to the type of data produced by each system. These values will be based on the uses to be made of the data and must be determined before a complete cost comparison is possible. The following discussions are only meant to introduce the reader to the relative acquisition costs and considerations which must be made for the envisioned airborne remote sensing system. Determining the value of the data from the alternative systems and preparing a complete cost/performance or cost/benefit analysis taking into account operating costs is beyond the scope of this current study effort.

9.1 Cost of Enlarging Ground Station Network

9.1.1 Number of Required Stations

For each pollutant a considerably larger amount of air quality data can be reported by either one run of the appropriate diffusion model or by a one hour aircraft overflight (with the appropriate sensors operating), than by the presently operating air quality ground stations. In order to acquire the same magnitude of data from ground stations as from the models, a ground station would have to be established for each receptor point specified in the corresponding model run. For the carbon monoxide model, this could be as many as 625 points spaced as close together as 125 meters. The equipment and staff required for such a large number of stations is beyond the resources of any local agency making it impossible for any agency to deploy such a network of air quality monitoring stations. Some of the airborne sensors can record data continuously while the aircraft covers 20 miles in only ten minutes. Again, one sees that it simply is not feasible to use ground stations to produce the same quantity of air quality data.

Government guidelines do exist for determining a reasonable number of ground stations for an air quality region. Computations based on these guidelines are discussed in the following pages, but it must be remembered that the computed number of stations would not be capable of producing the same magnitude of data that the aircraft overflights or diffusion modeling can produce. Rather, the number of ground stations which result from the following calculations must only be considered as the number of stations required to give a minimum picture of the air quality of the region.

In the Federal Register of November 25, 1971, the requirements for each Implementation Plan were given and provided for the establishment of air quality surveillance systems in each Air Quality Control Region. The minimum requirements for class I regions, such as Washington, D.C., are based on population. The following formulas were given in the

Federal Register[1] to compute the minimum number of continuous sulfur dioxide sites and the minimum number of continuous carbon monoxide sites:

Pollutant	Region Population	Number of Sites
Sulfur dioxide	Less than 100,000	1
	100,000- 5,000,000	1 + 0.15 per 100,000 population
	above 5,000,000	6 + 0.05 per 100,000 population
Carbon monoxide	Less than 100,000	1
	100,000- 5,000,000	1 + 0.15 per 100,000 population
	above 5,000,000	6 + 0.05 per 100,000 population

Based on 1970 census figures, the population of the National Capital Air Quality Control Region (AQCR) is 2,861,000. Using this figure and the formulas above, yields a result of a minimum of ten continuous carbon monoxide and ten continuous sulfur dioxide sites. Presently, there are ten carbon monoxide and nine sulfur dioxide continuous instruments being operated in the region. In the past the data from these sites have been spotty, at least in part due to instrument and recording equipment malfunctions. Although ten sites may be sufficient for monitoring the air quality in this region, our experience has been that ten stations are not sufficient to produce enough data for a reliable calibration of diffusion modeling runs, and certainly are insufficient for demonstrating existing patterns of air pollution over the city.

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1 Federal Register, 36FR228, (November 25) 1971.

Another set of equations for estimating the number of sites to be located in a region was given in "Guidelines: Air Quality Surveillance Networks" by the U.S. Environmental Protection Agency. These equations relate the number of stations to the degree of pollution and the land area of the region. The total number of required stations is the sum of the values computed for each of three subareas:

- Area wherein concentrations are higher than the ambient air quality standard (AREA 1)
- Area wherein concentrations are above background but less than the ambient standard (AREA 2)
- Area wherein concentrations are at background levels (AREA 3)

The equations are shown below:

Number of samplers for AREA 1 = $0.0965 \left(\frac{C_m - C_s}{C_s}\right)$ number of sq. km. in AREA 1

Number of samplers for AREA 2 = $0.0096 \left(\frac{C_s - C_b}{C_s}\right)$ number of sq. km. in AREA 2

Number of samplers for AREA 3 = 0.0004 number of sq. km. in AREA 3

where C_m = Value of maximum isopleth

C_s = Ambient air quality standard

C_b = Value of minimum isopleth

In order to obtain values for the maximum and minimum isopleths, the Implementation Plan for the District of Columbia was referred to. Appendices B and F contained maximum one-hour carbon monoxide and sulfur dioxide* values which have exceeded the standards, and these figures were used in the above equations.

The total area of the National Capital AQCR is 6024 square kilometers, but data are not available on what part of this total has air quality levels above standards or at background. Based on air quality figures included in the NCAQCR Implementation Plan and the results of the model runs, it was concluded that if any areas in the AQCR exceed the sulfur dioxide or carbon monoxide standards, that they are indeed small. Consequently, a figure of 50 square kilometers was estimated as the area exceeding standards and 1450 square kilometers was assumed to be the area where concentrations exceeded background but were below the standards. The remaining 4524 square miles were assumed to have only background concentrations of sulfur dioxide and carbon monoxide.

Based on the above information, the number of required samplers for sulfur dioxide and carbon monoxide were found to be:

Sulfur dioxide	AREA 1	1
	AREA 2	13
	AREA 3	2
	TOTAL	16
Carbon monoxide	AREA 1	1
	AREA 2	14
	AREA 3	2
	TOTAL	17

*DC has a one hour SO_2 standard of 0.323 ppm.

This is a total of 14 CO and SO_2 samplers more than are presently in operation, or a minimum of seven more sites.

9.1.2 Cost Per Ground Station

The cost figures of ground stations specified for the Regional Air Pollution Study (RAPS) were considered a good guide to the cost of installing and equiping new air quality stations. Two types of stations were considered for our analysis. The first was the most sophisticated type of station considered for RAPS which includes seven air quality instruments and a complete compliment of meteorological instruments. For the second type of system, those instruments that would not be needed for collection of data comparable to data recorded by the aircraft were eliminated. The instrument costs are broken down in Table 9-1 and represent the approximate average of currently available second generation instruments.

In Table 9-2, the costs of calibration equipment, spare parts, site preparation and shelter, and digital data terminal equipment are presented and the total initial cost of the two types of ground stations is calculated. The type 2 station which would be capable of recording the same kinds of data as the aircraft is estimated to be $29,000 cheaper to install than the more sophisticated type station. In the previous section it was determined that a minimum of 7 sites be added to the present monitoring network. Using the estimated cost of installing a type 2 station, the total cost of enlarging the ground station network would be $396,200. Additional costs would be incurred for the

TABLE 9-1

ESTIMATED INITIAL COSTS OF

AIR QUALITY AND METEOROLOGICAL INSTRUMENTS*

AIR QUALITY INSTRUMENTS	COST IN THOUSANDS OF DOLLARS	
	TYPE 1 STATION	TYPE 2 STATION
CO-Methane-Hydrocarbon	$ 7.4	$ 7.4
Hydrogen sulfide-SO_2	5.6	5.6
Total Sulfur	5.0	-
Ozone	4.2	4.2
Nitric oxide-oxides of nitrogen	6.8	6.8
Nephelometer	5.0	-
CO	3.0	3.0
Hi-Vol sampler	0.3	0.3
Hydrogen generator	0.7	0.7
TOTAL	$38.0	$28.0
METEOROLOGICAL INSTRUMENTS		
Temperature	$ 1.5	$ 1.5
Wind direction and speed	2.9	1.0
Pyranometer	1.0	-
Pressure tranducer	0.5	-
Mercury barometer	0.2	-
Net radiometer	0.8	-
Dew Point hygrometer	3.7	-
Rain-Snow gage	0.3	-
Wind Shield	0.1	-
TOTAL	$11.0	$ 2.5

*Based on the types of equipment being used in the St. Louis RAPS study and their estimated costs as reported in "Regional Air Pollution Study: A Prospectus Part IV-Management Plan."

TABLE 9-2

ESTIMATED TOTAL INITIAL

COST PER AIR QUALITY GROUND STATION*

STATION COMPONENT	COST IN THOUSANDS OF DOLLARS	
	TYPE 1 STATION	TYPE 2 STATION
Air Quality Instruments	$38.0	$28.0
Calibration Equipment/Accessories	8.3	7.7
Meteorological Instruments	11.0	2.5
Instrument Spare Parts	5.7	3.8
Site Preparation/Shelter	13.1	5.6
Digital Data Terminal Equipment	9.6	9.0
TOTAL	$85.7	$56.6

*Based on the types of equipment being used in the St. Louis RAPS study and their estimated costs as reported in "Regional Air Pollution Study: A Prospectus Part IV-Management Plan."

increased staff that would be needed to man the new stations and the increased administrative functions that would be needed to handle the larger network.

9.2 Cost of Running the Diffusion Models in Combination with an Enlarged Ground Station Network

The data collected by an air quality network of the size discussed above, could be supplemented by atmospheric diffusion modeling. The ground data could be used to calibrate the model, thus improving the accuracy of the model results. The spacing of the model receptors and the frequency of sampling aboard the aircraft could be adjusted so that the model results and the aircraft's recorded data were comparable.

The cost of running the diffusion models on a regular basis depends on many factors such as:

- How many models are to be run?
- Is there a computer available or would one need to be purchased or rented?
- Is staff available who could run the models or would additional staff have to be hired and trained?
- Are all the necessary models available and operational, or would new models have to be developed or modified to fit the specific requirements of this type of project?
- How often and how difficult would it be to change model inputs such as emission rates?

Some of the items required for installing a set of models can be quite costly. For example, development of a new model could cost anywhere from \$300,000 to \$1,000,000 or more depending on the level of complexity of the model. Assuming that six models will be run (each for a different pollutant), that five of the models are available and that the development of the sixth model will be relatively straightforward, that a computer will be available, that only one additional staff member had to be hired, and that changes to the existing models would be minimal, an estimate of the total cost of developing such a modeling system is shown below:

development of 1 model	\$500,000
1 additional staff for 1 year	20,000
minimal changes to existing models	3,000
	\$523,000

This estimate is extremely rough but can serve as a guide to the magnitude of the costs which would be incurred. It should be noted that the cost of developing a new model would be a one time cost, which would not be incurred by each city using the program.

9.3 Cost of an Aircraft Air Quality Monitoring System

The cost of operating an aircraft for the types of overflights considered in this study has already been discussed in Section 6.3, and very little information is currently available on the cost of the instruments under consideration. The major problem in determining the cost of these instruments is that they are still in the development stages. Any estimate of their cost is based on the production of one unit and reflects the total cost of the research and development which has taken place. A rough estimate of \$1.5 million for the cost of the first HSI instrument, was obtained from Dr. C. B. Farmer. That would make the total aircraft system seem completely unfeasible from an economic point of view. However, Dr. Farmer also said that the cost of the second such instrument would be more in the range of $150,000. Because the five other instruments are less complex, it is probable that they might cost less. It is expected that the total cost of the six instruments would be less than $900,000. As already discussed, the total cost of enlarging the ground network and installing the diffusion models could run in the neighborhood of $919,000. The cost estimated for installing the diffusion models is very flexible depending on the other factors mentioned in the previous section.

If an aircraft already owned by NASA or if an aircraft is rented, there will be no acquisition costs for the aircraft. Thus, the cost of the airborne remote sensing system is in the same range as the cost of enlarging the ground station network and installing a diffusion modeling system. To produce a detailed picture of the air quality over the Washington, D.C. area by either system can be expected to cost as much as one million dollars. However, before the use of the airborne remote sensing system is operationally feasible, problems such as vertical resolution and computer data handling mentioned in earlier sections, must be overcome.

Both systems would have some instrument downtime, but in addition the airborne system will have downtime due to bad weather preventing the flights from being made. The cost penalty resulting from non-operation during bad weather can not be estimated at this time. However, the cost benefit of another factor related to the aircraft system will far outweigh this cost penalty. The aircraft system does not have to be confined to operating over the Washington area. It could be used concurrently for monitoring over other nearby cities such as Baltimore. This would spread the cost of procuring the airborne sensors over several projects, and improve the economic feasibility of the airborne remote sensing system. Similarly, cost of developing new models could be shared by more than one project, thus decreasing the cost to each.

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